Hi-Z TECHNOLOGY, INC.

THERMOELECTRIC MATERIALS • DEVICES • SYSTEMS

HZ-08084-1

PRELIMINARY DESIGN OF A MINIATURE THERMOELECTRIC GENERATOR

FINAL REPORT

"Approved for public release; distribution is unlimited".

JOHN C. BASS

Prepared Under Grant Contract Number

DAAK70-93-C-0062

for

THE U. S. ARMY

August 8, 1994

6373 Nancy Ridge Drive, San Diego, CA 92121-2247 • Telephone (619) 535-9343 • FAX (619) 535-9350

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List of Abbreviations

MTBF	Meantime before failure
Major ATON	Major Aid to Navigation
DF-2, DF-A	Diesel fuel grades
JP-8, JP-5	Jet fuel grades
I.R.	Infra red
VDC	Volts, Direct Current
VAC	Volts, Alternating current
db	Decibel
ft^3	cubic feet
lb	Pound
W	Watt
MIL-STD	Military standard
TEG	Thermoelectric Generator
GA	General Atomic Company
BiTe	Bismuth Telluride
°C	degrees Centigrade
°F	degrees Farenheit
PbSnTe	Lead-Tin-telluride alloy
ΔT	Temperature difference
kW	kilowatt
KAPL	Knolls Atomic Power Laboratory
ITR	International Thermal Research
psig	pounds per square inch
RPM	resolutions per minute
FMI	Fluid Metering, Inc.
Hz	Hertz (cycles per second)
PCV	Power Conversion Unit
%	Percent
gal/hr	gallons per hour
PbTe	Lead-Telluride
w/cm^2	watts per square centimeter
μ	10^{-6} meters
yr	year

SUMMARY

This is the report of a Phase I SBIR to study the design of a small, lightweight thermoelectric generator which will produce 500 Watts of 60 cycle alternating current power. A set of generator design criteria which were developed in the original proposal are reported. This is followed by a brief survey of the current available thermoelectric technology which reports that while several attempts to develop thermoelectric generator in various power ranges, none of these systems are currently available. Only one of the commercially available thermoelectric generators can burn liquid fuel such as DF-2, DF-A, and JP-8.

The various types of thermopiles is discussed. The continued development of a metallurgically bonded planar lead-telluride module which is segmented to obtain maximum conversion efficiency is recommended.

The design details of a 500 Watt generator are given. This preliminary generator design nearly meets the design goals established, however, the design requires more detailed engineering to reach those goals. We believe those goals can be met in Phase II. The current estimate of fuel consumption is about 0.41 gal/hr.

A discussion of the infra-red signature and an estimate of the overall system reliability are discussed.

1.0 Introduction

The U.S. Marine Corps has need for power sources in the 500 Watt area. These sources should be highly reliable, small, lightweight, signal suppressed, and be able to use liquid fuels, preferably Diesel, as the energy source. The desire to burn Diesel stems from the Armed Services desire to use Diesel as their main fuel source. Other fuels such as gasoline create a logistic problem and therefore, is to be avoided if at all possible.

There are currently no known power supplies of this type commercially available on the open market. The Diesel motor generator sets that are available have higher power outputs and typically have a rather low mean-time before failure (MTBF). Earlier contact with Army personnel indicate that the MTBF of small portable Diesel motor/generator sets were about 175 hours. Similar experience has been reported by the U.S. Coast Guard in both their Major Aids to Navigation, Major ATON, and their Weather Data Buoys.

The purpose of this study is to develop a preliminary design for a 500 Watt thermoelectric generator. This generator must be capable of operating on logistically available liquid fuels such as DF-2, DF-A and JP8. The burner for the generator should be capable of operation with virtually any liquid fuel. It should be a quiet power source, have high reliability, and a low I.R. signature.

2.0 Program Goals

The several program design goals for the 500 Watt thermoelectric generator are:

Voltage Output	24 VDC/110VAC
Power	500 Watt @ 110 VAC
	550 Watt @ 24 VDC
Reliability	10,000 hrs MTBF
Maintenance	1 hr/5000 hr operation
Noise	≤ 50 db (A) @ 1 meter
Size	≤ 1.5 ft^3
Weight	≤ 45 lb (DRY)
Time to 80% Power	≤ 3 minutes

Other features that are included in the design are:

Fuel	Multiple Liquid Fuels including JP-8, DF-2, JP5
TEG Modules	Lead-Telluride, both bonded and unbonded will be considered
Cooling System	Air Cooled
Control System	Automatic Start, Stop and Control
Power Conditioner	Commercially Available Equipment
Thermal Signature	Low I.R. Signature
Housing	Provide Easy Maintenance Access Meet Shock and Vibration per MIL-STD-810
Sound	Inaudible at 50 ft.

An isometric drawing of the 500W generator design developed during Phase I of the contract to meet these requirements is shown in Figure 2.1

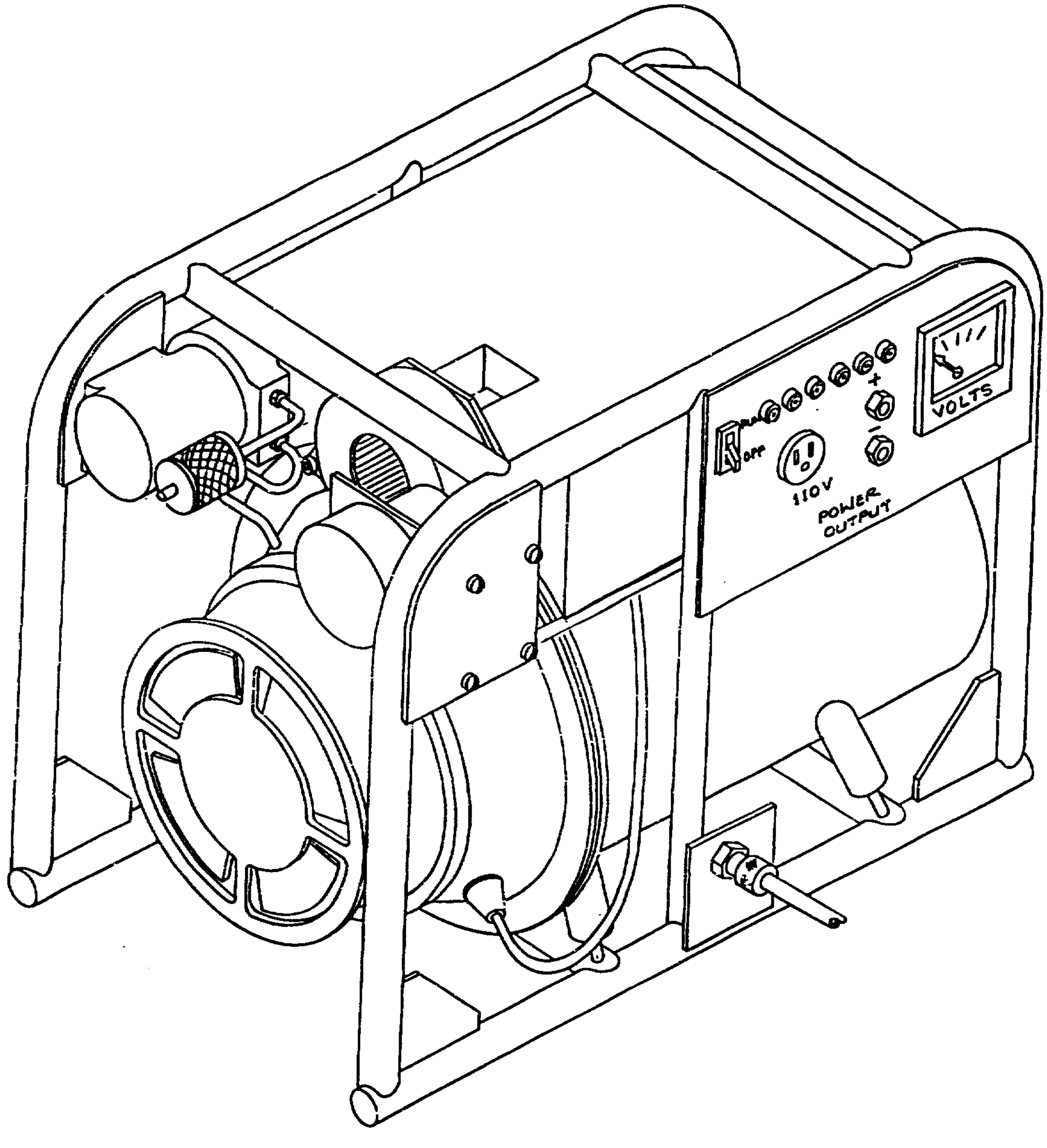


Figure 2.1 Isometric View of 500W Generator

3.0 Review of Commercially Available Thermoelectric Generators

A review was made of commercially available thermoelectric generators (TEGs) for applicability to the U.S. Marine Corps requirements. There are currently only two major vendors of commercial TEGs: Teledyne Energy Systems (Teledyne) in the United States, and Global Thermoelectric Power Systems, Limited (Global), in Canada. Each vendor offers a number of TEGs of varying capacity up to ~500 watts electrical. The generators from these companies are each based on different burner and TE module technologies. Each of these technologies is briefly reviewed below.

Other companies who work in the thermoelectric power field include: Thermoelectric Concepts located in Calgary, Canada who is currently introducing a 10W thermoelectric generator; General Atomics, Inc. (GA), who did the original development work on the improved 1.5 kW Generator Program for the Army in the early 1980's; Thermal Electron Corporation's TECOGEN division, who did some silicon-germanium thermopile development work for the Army in the mid 1980's and has more recently participated in thermoelectric materials studies for the space program. The Army's thermoelectric development work was not completed due to lack of government funding.

Hi-Z Technologies, Inc. is currently working in the thermoelectric waste heat market area and is developing a 20 Watt bismuth-telluride generator. None of the other thermoelectric companies presently produces a line of commercially available thermoelectric generators that would be of interest in the Marine Corps current program.

All of the companies discussed potentially have the capability, capacity, and technology to produce a large thermoelectric generator provided sufficient funding is available for development.

3.1 Teledyne TEGs

Teledyne's commercial TEGs use BiTe thermoelectric semiconductor materials to convert heat to electricity. This material has a relatively high efficiency at low temperatures. The heat for the Teledyne generators is provided by burning either butane, propane, or natural gas in a catalytic burner. No diesel fueled generators are known to be produced commercially by Teledyne at the present time. The catalytic burner used by Teledyne provides efficient combustion at relatively low (~800°C) temperatures. The overall conversion efficiency for these generators (fuel energy content to electrical power output) ranges between 2 to 4 percent. A catalytic burner is used because BiTe's normal operating temperature limit on the hot junctions is 280°C (535°F) and Teledyne's low heat flux modules which are large relative to their power output, are designed to maintain low temperature operation and natural convection cooling. Teledyne's commercial TEG uses a pressurized gas in the fuel system, which eliminates all moving parts and increases system reliability. Table 3.1 presents a summary of specification for Teledyne's line of commercial TEGs. These generators are built up by assembling multiple 10 Watt units to make a single unit of higher power.

Teledyne designed and built lead-telluride TEGs for the Army in the 1970s and early 1980s. The output power of those generators range from less than 100 Watts to about 500 Watts. None of these generators is currently known to be available to the commercial market.

3.2 Global TEGs

Global commercial TEGs currently employ PbSnTe thermoelectric alloys exclusively as the semiconductor for converting heat to electricity. PbSnTe hot junctions are limited to ~650°C (1202°F), thus permitting a large temperature difference (ΔT) from the hot to the cold junctions. Heat for most of Global's generators is provide by burning butane, propane or natural gas in all but one generator in Global's line of commercial TEGs. This one generator, the model 7120, burns Diesel

Table 3.1 Summary of Teledyne's Thermoelectric Generators

TELAN

Generator Model	Electrical Spec. (Minimums) P W	E V	I A	Std. Avail. Electric Outputs: Power Condition Code	Standard Wiring Code	P W	E V	I A	Fuel Consumption: Propane Butane Lb./Wk. (Kg/Wk)	Natural Gas MCF/Wk (M³/Wk)	Size and Weight: H In. (cm)	W In. (cm)	L In. (cm)	Wt. Lb. (Kg)
Telan 2T1	10	4.8	2.1	12CL 24CL 48CL	10S 10S 10S	8 8 8	12 24 48	.67 .33 .17	11.2 (5.1)	.23 (6.5)	17 (43)	11 (28)	19 (48)	33 (15)
Telan 2T2	20	9.6	2.1	12XL * 12CL * 24CL 48CL	20S 20S 20S 20S	19 17 17 17	12 12 24 48	1.58 1.41 .71 .35	22.4 (10.2)	.46 (13.1)	17 (43)	25 (64)	14 (36)	52 (24)
Telan 2T3	30	14.4	2.1	12XL 24CL 48CL	30S 30S 30S	30 25 25	12 24 48	2.50 1.04 .52	33.6 (15.3)	.69 (19.6)	17 (43)	25 (64)	23 (58)	73 (33)
Telan 2T4	40	19.2	2.1	12XL 24XL 24CL 48CL	20S 40S 40S 40S	36 36 34 34	12 24 24 48	3.0 1.5 1.42 .70	44.8 (20.4)	.92 (26.1)	17 (43)	25 (64)	22 (56)	93 (42)
Telan 2T5	50	24.0	2.1	12XL 24XL 48CL	25S 50S 50S	50 50 42	12 24 48	4.16 2.08 .87	56.0 (25.4)	1.15 (32.6)	17 (43)	25 (64)	31 (79)	112 (51)
Telan 2T6	60	28.8	2.1	12XL 24XL 48CL	30S 60S 60S	60 60 51	12 24 48	5.00 2.50 1.06	67.2 (30.5)	1.38 (39.1)	17 (43)	25 (64)	30 (76)	130 (59)
Telan 2T7	70	33.6	2.1	12XL 24XL 48CL	35S 70S 70S	68 68 59	12 24 48	5.67 2.83 1.23	78.4 (35.6)	1.61 (45.6)	17 (43)	25 (64)	39 (99)	149 (68)
Telan 2T8	80	38.4	2.1	12XL 24XL 48XL	20S 40S 80S	79 74 73	12 24 48	6.58 3.08 1.52	89.6 (40.7)	1.84 (52.2)	17 (43)	25 (64)	38 (97)	170 (77)
Telan 2T9	90	43.2	2.1	12XL 24XL 48XL	30S 45S 90S	90 89 89	12 24 48	7.50 3.71 1.85	100.8 (45.8)	2.07 (58.7)	17 (43)	25 (64)	47 (119)	189 (86)

* For best efficiency, use the 2T2 12XL generator with load voltages below 12.6 VDC. Use the 12 CL for voltages from 12.6 to 16 VDC.

* For best efficience, use the 2T4 24XL generator with load voltages below 24 VDC. Use the 24CL for voltages from 24 to 31 VDC.

DECAP

Generator Model	Electrical Spec Matched Load: W	V	Current	R.	80% Power – Off Match Load Resistance Range: W	V	I	R	V	I	R	Natural Gas Fuel Consumption MCF/Week
2DT40N10S	40	4.8	8.4	.57	32	2.5	12.8	0.20	7.1	4.5	1.58	.92
2DT40N20S	40	9.6	4.2	2.29	32	5.0	6.4	0.78	14.2	2.3	6.31	.92
2DT60N10S	60	4.8	12.6	.38	48	2.5	19.2	0.13	7.1	6.8	1.05	1.38
2DT60N20S	60	9.6	6.3	1.52	48	5.0	9.6	0.52	14.2	3.4	4.20	1.38
2DT60N30S	60	14.4	4.2	3.42	48	7.5	6.4	1.17	21.3	2.3	9.46	1.38
2DT80N10S	80	4.8	16.8	.29	64	2.5	25.6	0.10	7.1	9.0	0.79	1.84
2DT80N20S	80	9.6	8.4	1.14	64	5.0	12.8	0.39	14.1	4.5	3.15	1.84
2DT80N40S	80	19.2	4.2	4.57	64	10.0	6.4	1.55	28.4	2.3	12.62	1.84

fuel and other liquid hydrocarbons.

The burners used by Global provide heat at higher combustion temperature (1000°C to 1100°C) than the catalytic burners used by Teledyne, and thus they provide a better match to the higher temperature and heat flux capability of the PbSnTe. Higher temperatures used by Global result in conversion efficiencies (fuel energy content to electrical output) of approximately 4.7 percent, when the gaseous fuels are used. More parasitic power is consumed in the Diesel fueled version to run a spinning disc atomizer, a combustion air blower, a fuel pump and a forced convection cooling fan. The system efficiency of their Diesel fueled unit is thereby reduced to ~2.0%. Differences in efficiency are ultimately reflected in the fuel consumption rate.

PbSnTe thermoelectric materials must be protected from oxidation during operation and thus the Global thermoelements are hermetically sealed in inert gas containers that are designed to have a life of at least 20 years. Modules and combustion chambers have >10 year life, while the spinning disc atomizer, combustion air blower motor, fuel pump and cooling fans in Global's diesel-fuel TEGs have greater than 2000 hour MTBF, according to the vendor. Table 3.2 presents a summary of specifications for the current Global line of TEGs which is built up by assembling multiple 50W units around a single burner sized for the particular generator output.

The high temperature burner used in the Global TEGs to support the lead-telluride materials leads to greater stack heat losses. Depending on system economic considerations, some of this energy could be recovered to increase the overall system conversion efficiency. Such energy recovery is usually done through the use of a recuperator in the system. Recovery of heat in a recuperator is usually not economically practical in a small 120 W TEG, however, it becomes increasingly desirable as the output power of the system is increased.

Global designed and produced two 2 kW thermopiles for the Army in 1985-86 time period under contract DAAL01-85-C-0465. These thermopiles were liquid cooled and the burner fuel was propane.

Table 3.2 Summary of Global Thermoelectric's Thermoelectric Generators

System Voltage	Power (Watts)	PEM System No.	Available Heat BTU/HR-KCAL/HR	Air Flow CFM-M³/Min	Fuel Consumption Gals/Day-Kilos/Day (Propane)	Net Weight Lbs.-Kilos
	50	1-5060-12 PEM	3,000 - 756	30 - .85	1.5 - 2.9	205 - 93
	108	1-5120-12 PEM	6,000 - 1,512	83 - 2.3	3.0 - 5.7	260 - 118
12-18 VDC	120	2-5060-12 PEM	6,000 - 1,512	60 - 1.7	3.0 - 5.7	285 - 129
	240	2-5120-12 PEM	12,000 - 3,024	165 - 4.6	6.0 - 11.4	390 - 177
	350	3-5120-12 PEM	18,000 - 4,548	250 - 7.0	9.0 - 17.1	650 - 296
	480	4-5120-12 PEM	24,000 - 6,048	330 - 9.2	12.0 - 22.8	780 - 354
	50	1-5060-24 PEM	3,000 - 756	30 - .85	1.5 - 2.9	205 - 93
	108	1-5120-24 PEM	6,000 - 1,512	83 - 2.3	3.0 - 5.7	260 - 118
24-30 VDC	216	2-5120-24 PEM	12,000 - 3,024	165 - 4.6	6.0 - 11.4	390 - 177
	355	3-5120-24 PEM	18,000 - 4,548	250 - 7.0	9.0 - 17.1	650 - 296
	480	4-5120-24 PEM	24,000 - 6,048	330 - 9.2	12.0 - 22.8	780 - 354
	50	1-5060-48 PEM	3,000 - 756	30 - .85	1.5 - 2.9	205 - 93
	108	1-5120-48 PEM	6,000 - 1,512	83 - 2.3	3.0 - 5.7	260 - 118
48-60 VDC	216	2-5120-48 PEM	12,000 - 3,024	165 - 4.6	6.0 - 11.4	390 - 177
	324	3-5120-48 PEM	18,000 - 4,548	250 - 7.0	9.0 - 17.1	650 - 296
	432	4-5120-48 PEM	24,000 - 6,048	330 - 9.2	12.0 - 22.8	780 - 354

An attempt was made during an earlier program to find out what happened to these 2 kW thermopiles following the demise of the Army's thermoelectric development program. We found that the Army had declared the 2 kW thermopiles surplus and they were subsequently transferred to the Knolls Atomic Power Laboratory (KAPL), where they are currently being used on a classified program.

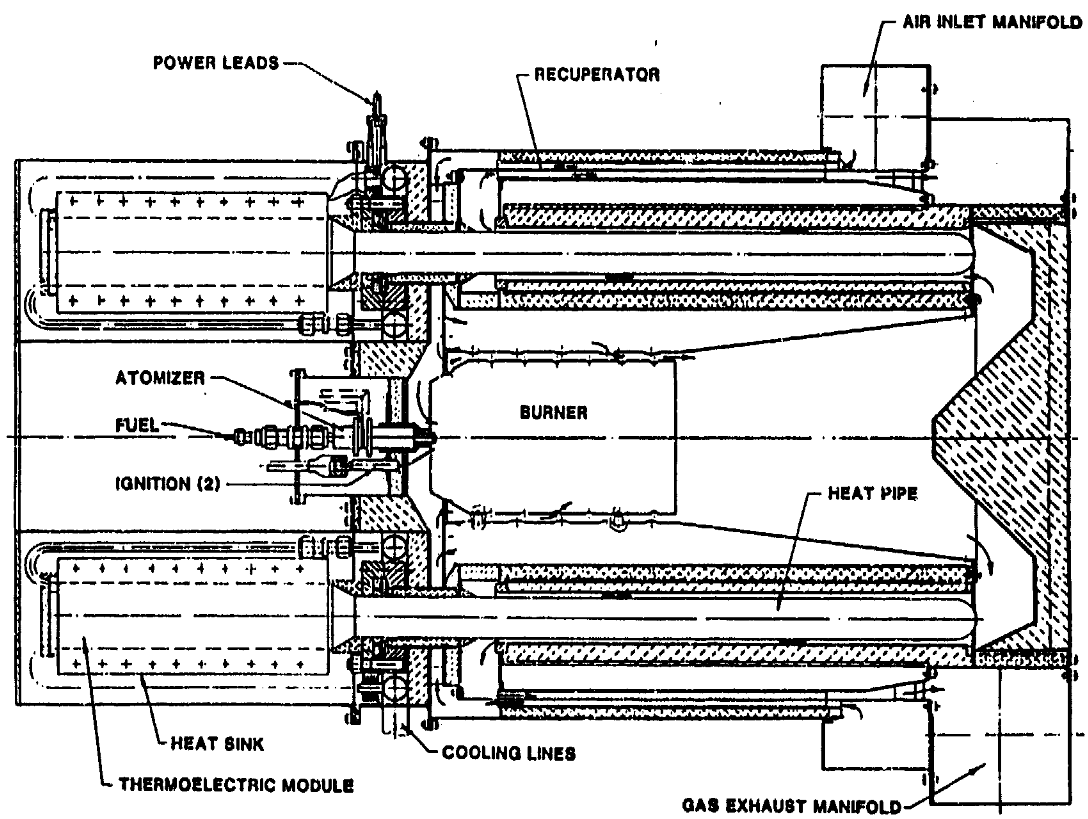
3.3 GA 1.5 kW Generator

In 1982, General Atomic Company (GA) started a program to develop an improved thermoelectric generator for the U.S. Army at Fort Monmouth. The purpose of this program was to develop a modular thermoelectric system which could be used in generator systems over a range of power outputs of from 1.5 kW to 10 kW. The generator was to have improved thermal efficiency, be easily expandable and meet the requirements of the Army's SSLEEP ROC program to develop a silent reliable electric power source to replace their diesel engine generator sets. The Army's small

Diesel generator sets were reported to have an MTBF of about 175 hours which required that they be deployed in pairs to achieve a reasonable reliability.

The concept developed at GA to meet these requirements is shown in Figure 3.1. The generator consisted of a central located vortex stabilized Diesel fuel burner surrounded by eight potassium heat pipes. Each of the eight heat pipes was used to transport and concentrate the energy from the burner combustion gas to six planar thermoelectric modules mounted on the flattened side of the end of the heat pipe shown in Figure 3.2. The modules were held in place against the heat pipe by two spring loaded liquid cooled heat exchange blocks. An annular plate fin type of recuperator was wrapped around the outside of the generator to transfer energy from the exhaust gas to the inlet air to improve fuel efficiency.

Figure 3.1 Power Conversion Unit Layout From GA's 1500W(e) Thermoelectric Generator CIRCA 1983



A prototype power conversion unit for the improved 1.5 kW generator was built (3.1). The system was not completely developed because the Army's program requirements changed prior to the completion of the program and they ran out of funding. However, the planar lead-telluride modules (shown in Figure 3.3) for the generator were built and tested. The heat pipe development for the prototype unit was also completed, (3.2) as was the development of most of the system components, including the burner and the recuperator, when the program was terminated. Much of the information is still available at Hi-Z, including the construction details of the lead-telluride module.

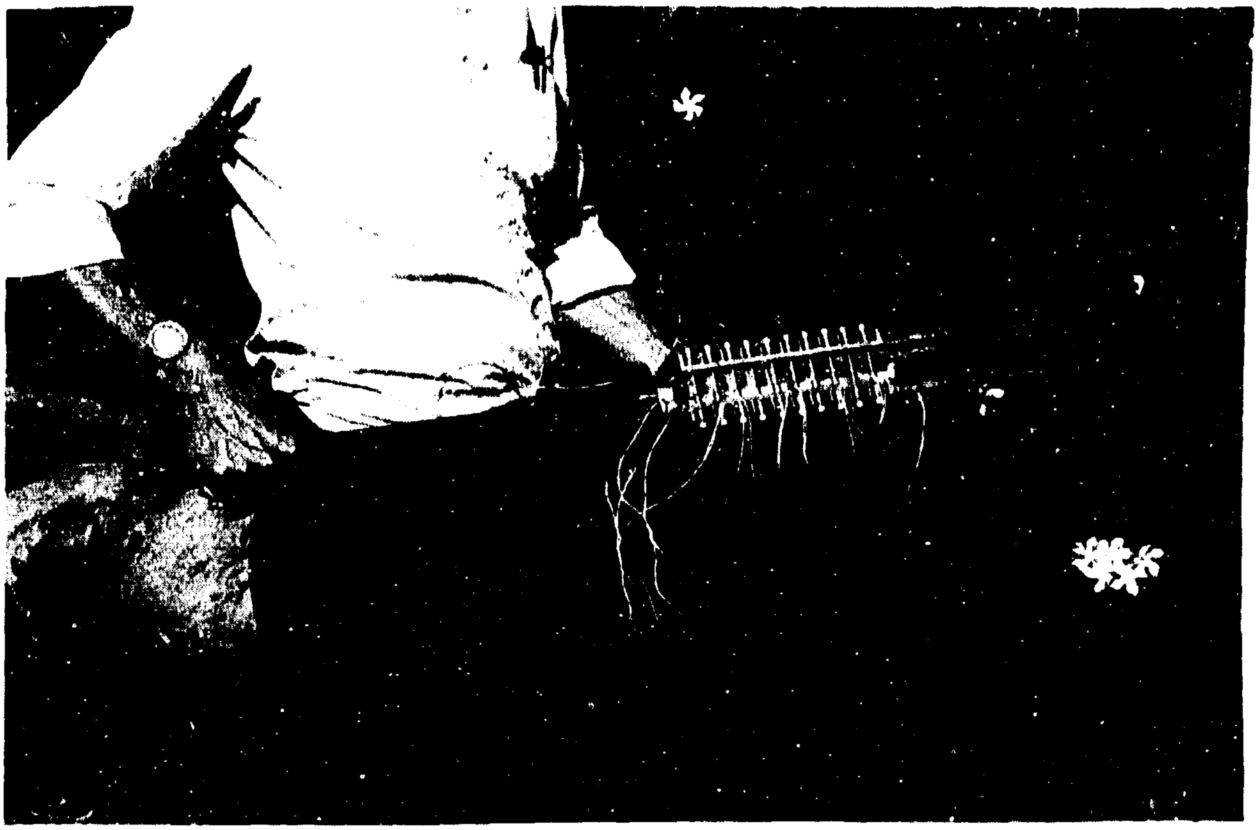


Figure 3.2 250W Heat Pipe, Thermoelectric modules, and Heat Sinks from GA's 1500W Thermelectric Generator

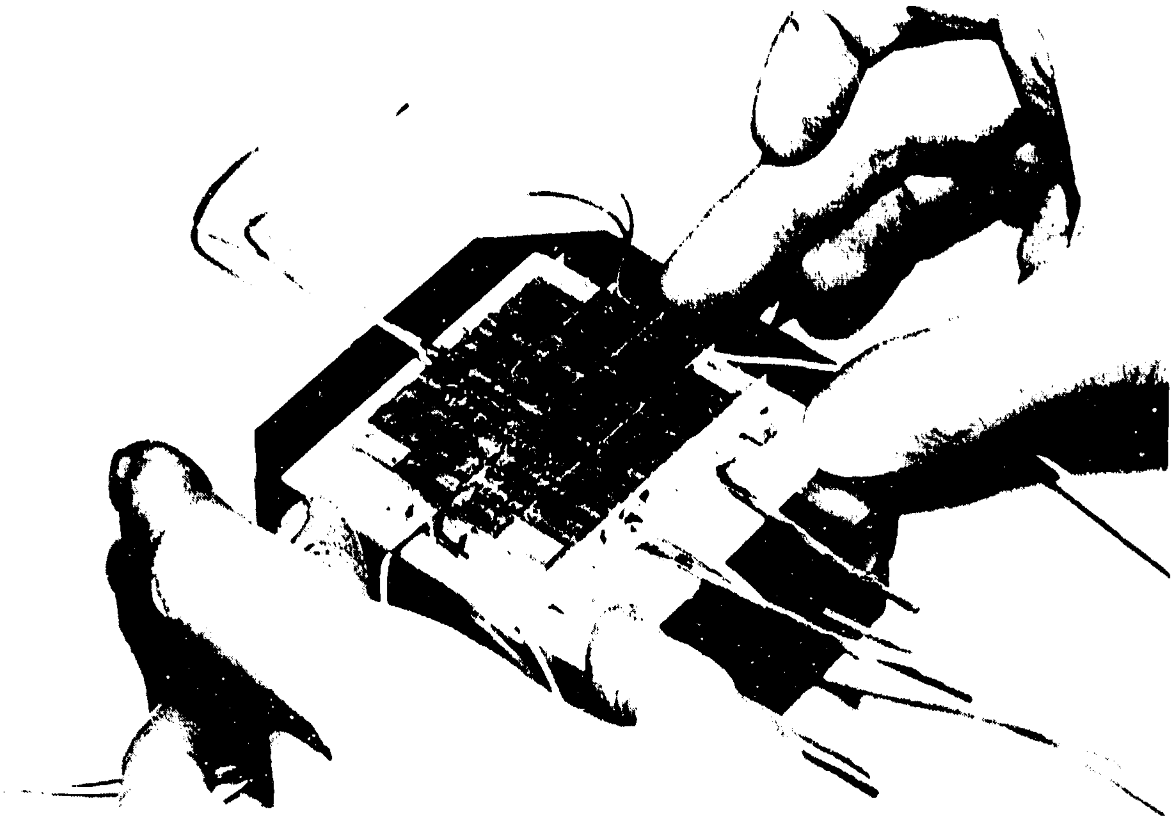


Figure 3.3 General Atomic Planar 42 Watt Lead Telluride Module with Test Thermocouples Attached

4.0 Thermopile Type

The type of thermopile construction used in a particular generator varies depending on the thermoelectric material used and the manufacturer. The two most popular approaches currently used can be classified as either planar or radial.

4.1 Planar Thermopiles

Both Hi-Z and Teledyne use variations of the planar arrangement for their bismuth-telluride thermoelectric modules. Examples of these modules are shown in Figures 4.1 and 4.2. The Teledyne module (Figure 4.1), which occupies a volume of 1.355 in^3. produce 8 Watts at 2.4 V DC. The Hi-Z module, which occupies a volume of 0.968 in^3, produces 13 watts at 1.8 V DC. Both modules use aluminum contacts to connect the thermoelements within the module.

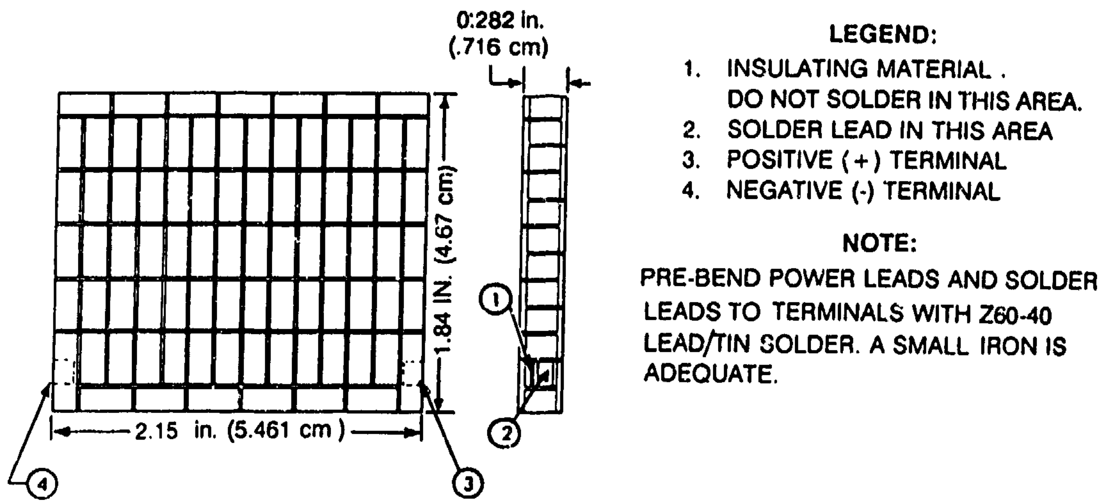


Figure 4.1 Teledyne Planar 8 Watt Bismuth Telluride Module

The principals of Hi-Z also developed and patented (4.2) a planar lead-telluride module, which was shown in Figure 3.3, while they were at GA. The construction of this module is quite different from that of the bismuth-telluride planar modules in that the components of the module are not metallurgically bonded. As a result, the module must be kept under a compressive load at all times to minimize the thermal and electrical contact resistance. This module incorporated copper felt pads as complement members on the cold side of each element to insure application of uniform pressure across the module. An exploded view of the 42 watt module construction is shown in Figure 4.2.

Global also manufactures a planar version of a lead-telluride module. This module, shown in Figure 4.3, is actually is a planar arrangement of the same elements and mechanical components used in their radial thermopile design which will be discussed later.

Hi-Z worked developing a bonded lead-telluride as part of a development program for the U.S. Coast Guard to design and build a 1.5 kW thermoelectric generator for their major aids-to-navigation (Major ATON). Unfortunately this program had to be terminated when the Coast Guard found that they did not have the funding necessary to complete the contracted work.

The bonded Hi-Z module featured segmented thermoelectric legs for both the N and P materials. Segmentation was used to increase the thermal to electric conversion efficiency and consists of a combination of two lead-telluride alloys to form the N leg while both P lead-telluride and P bismuth-telluride segmented together to form the P leg. Development of segmentation techniques for both legs was completed during the Coast Guard program. Some work remains to complete the element bonding of the electric contacts which connect the N and P legs in order to complete the module development.

Hi-Z recommends that the bonded module development started under the Coast Guard 1.5 kW program be completed during the final part of Phase II to build a 500 Watt generator. This will provide a thermoelectric module which is less costly because it is much easier to handle during assembly and it will also provide the highest conversion efficiency.

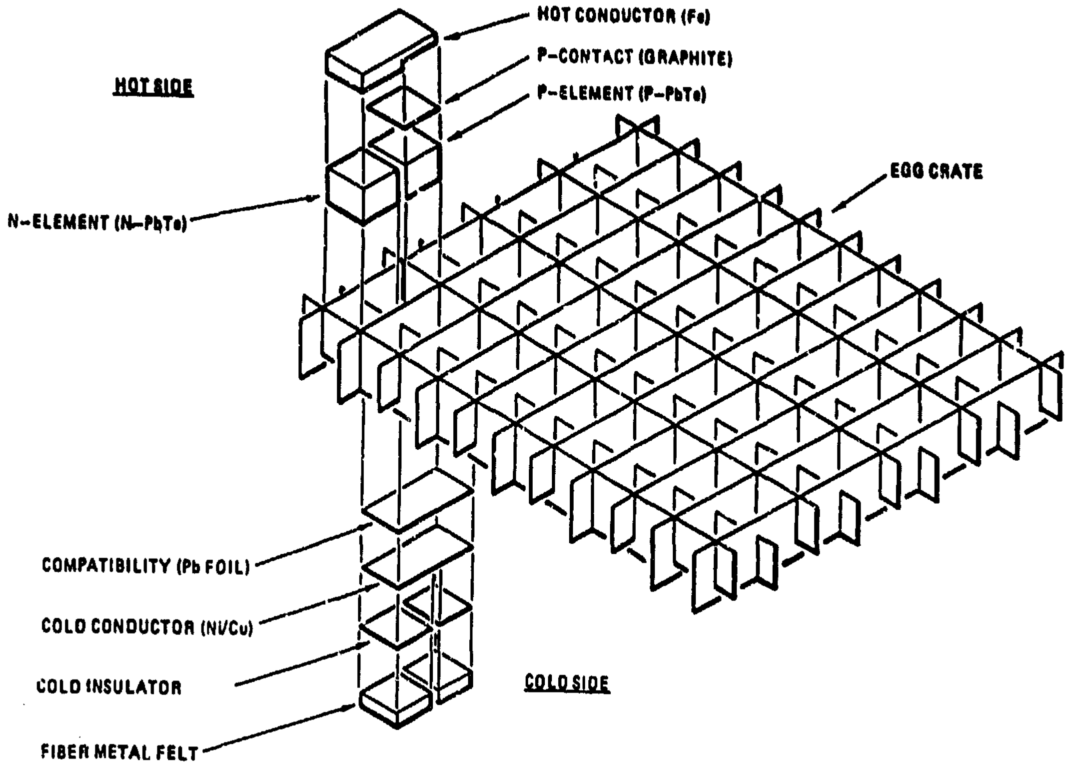


Figure 4.3 Construction of General Atomic's Lead Telluride Module

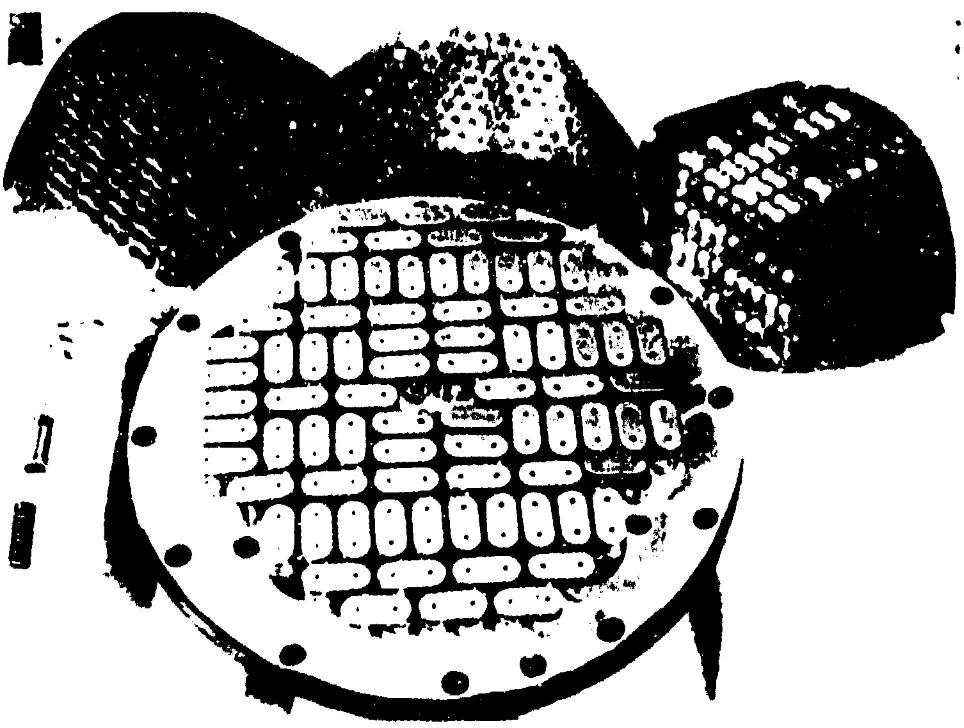


Figure 4.3 Global's Planar Lead Telluride Module

4.2 Radial Thermopile

The radial thermopile is constructed using several linear assemblies of individual N and P thermoelectric assembled in strings placed parallel to the axis of the generator. This arrangement places the elements in a radial orientation. The components are located in a follower block in one or more rows which run the length of the burner. The components for one couple which are not bonded together, as shown in Figure 4.4, includes a hot strap which electrically connects the N and P legs to the adjacent couple, two thermoelectric elements (one N and one P), a cold strap which connects the couple, two followers through which heat is transferred and a load is applied to the elements, two loading springs which fit inside both the follower and the follower block, to electric insulators, and the follower block. The hot strap and the follower are respectively compressed between the outer surface of the hot support structure and inside surface of the heat sink. This construction leads to high assembly cost because of handling the unbonded components and a difficult heat transfer situation because the reject heat must be conducted axially through the hollow element follower then radially through a gap filled with thermal grease into the follower block and then through another contact resistance to the heat sink.

The use of the planar or flat version of the radial elements (see Figure 4.3) eliminates the hot rails but suffers from the same heat transfer problems on the cold side. However, the assembly of the planar modules is easier than the radial ones. The power level that a single planar version of the radial module can be designed to produce is probably restricted for practical structural and heat transfer reasons to a few hundred (100 to 200) watts of electrical power.

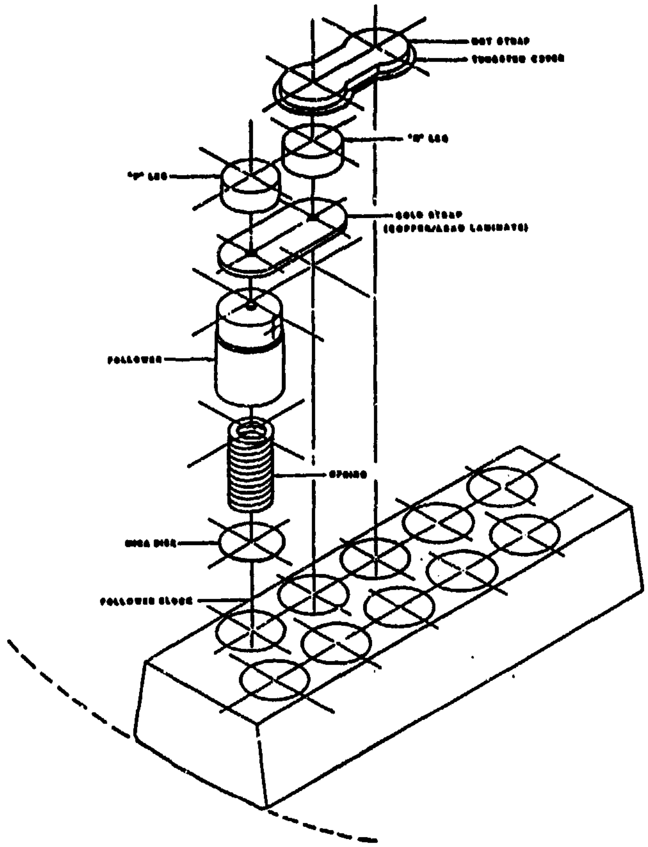


Figure 4.4 Components of a Radial Lead Telluride Module

5.0 Burners

The liquid hydrocarbon fuel burner represents one of the major potential problem areas with respect to the successful development of a thermoelectric generator with high reliability and low maintenance requirements such as is required by the Marine Corps for the 500 Watt TEG.

With the exception of the Global Model 7120, all of the information that we have received to date indicates that commercially available thermoelectric generators burn gaseous fuels such as propane, butane, or natural gas. The Global Model 7120 which has an output of 150 W is capable of burning various Diesel fuels as well as kerosene and JP-4 jet fuel.

One source of burner reliability problems is that a low flow(<1 gal/hr) liquid fuel burner such as would be required for the 500 Watt generator is subject to plugging by the various types of fuel atomizers used in liquid fuel burners. The plugging problem can be caused when fuel which has been stored for a long period of time (more than 1 year). This fuel can become contaminated or grow organic matter so that it becomes increasingly difficult to use as the fuel flow rate requirements decrease. The reason is that most conventional atomizers require ever smaller, and more easily clogged, fuel orifices and passages as the fuel flow rate decreases.

The thermoelectric generators built for the U.S. Army during the 1970's and early 1980's by Teledyne, 3M Company (the precursor to Global) and Global, were required to burn liquid hydrocarbon fuels. Almost all of these units used ultrasonic fuel atomizers — which do not require the small orifices associated with most other types of fuel nozzles. Ultrasonic nozzles, however, present their own set of reliability problems. They are subject to failures (Reference 5.1) which may occur in either the piezoelectric crystals, as shown in Figure 5.1, or power supplies and in the logic circuits used to drive the ultrasonic nozzles.

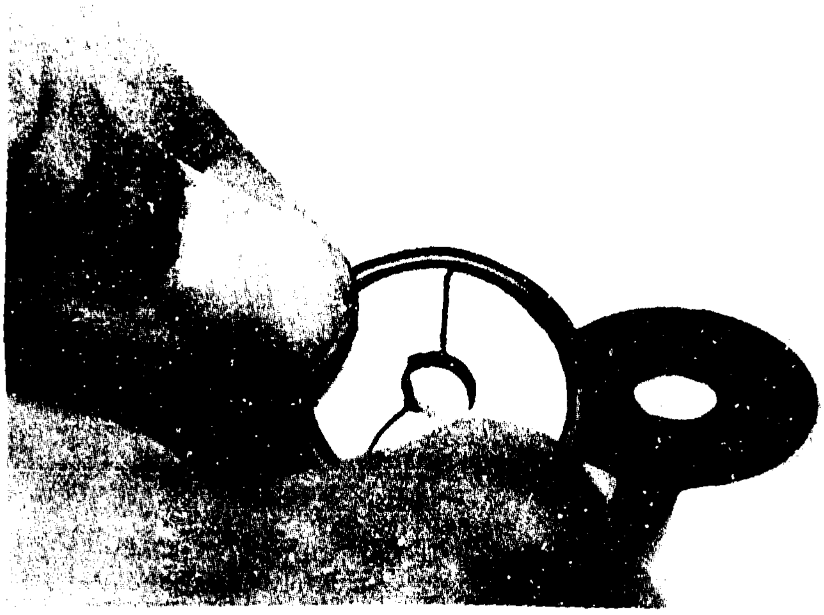


Figure 5.1 Components of Failed Ultrasonic Atomizer

Discussions with personnel from Global indicate that for their model 7120 Global has abandoned the use of ultrasonic nozzles for fuel atomization in favor of what they call "spinning disk" technology. Like the ultrasonic nozzle, the spinning disk does not require the small orifices of a typical spray nozzle and is reported to provide the degree of atomization necessary for clean efficient liquid fuel combustion. We do not have an quantitative information of the spinning disk burner although similar units have been used in home oil burners and Diesel fired vehicle heaters for several years.

Two other burner technologies may be useful in the in the development of a high reliability liquid fuel burner. The first is a "blue flame" burner developed by International Thermal Research, Limited (ITR) of Richmond, British Columbia, Canada, and the second is a burner developed by Babbington Engineering Inc., of McLean, Virginia. The ITR Diesel fuel burner uses an air-aspirated nozzle and has a built-in gassifier so that the flame actually burns blue like a gas flame. The other burner built by Babbington also uses a proprietary air-aspirated nozzle technology.

We do not have any details on the operation of the ITR burner, however, one might expect that there may be some difficulty over time because of the possible build up of the deposits from some of the higher temperature fractions of a fuel like Diesel fuel. This is suspected because Diesel fuel is made up of a large number of complex hydrocarbons, some of which have very high boiling point.

The Babbington burner was tested briefly by the U.S. Army ERADCOM at Ft. Monmouth, NJ for possible use in thermoelectric generators. The results of these tests were reported to be favorable by Dr. Guido Guazzoni, who was in charge of thermoelectric development at Ft. Monmouth at the time. He reported that the burner appeared to be very reliable and recommended it be considered for use in liquid fueled thermoelectric systems of the future. However, these tests were conducted in a laboratory under laboratory conditions.

The Babbington burner system shown schematically in Figure 5.2 was inspired by the liquid "nebulizer" used in the medical field to add moisture to breathing air. Fuel in the Babbington burner is pumped to the atomizer through a relatively large diameter tube and is directed to flow over a spherical or hemispherical surface. The surface tension causes the liquid to spread out over the surface of the sphere in a thin film. Air at about 15 psi is introduced into the inside of the sphere and escapes through a small slit located on one side near the sphere's equator. The slit is narrow enough that the surface tension of the liquid allows it to bridge the slit. The air within the sphere exits through the slit, breaking the thin film of liquid into small (approximately 1-10 micron diameter) particles. The fuel particles are blown away from the spherical surface where they can be mixed with air and easily ignited and burned. The remaining fuel flow off the bottom of the sphere is collected and returned to the system.

One of the major advantages of the Babbington burner is that it has a large turndown ratio, i.e., it can atomize fuel over a wide range of heat outputs. The amount of fuel atomized is controlled by regulating the pressure of the air introduced to the atomizing sphere. However, the size of the atomized fuel particles should increase as the air flow is decreased.

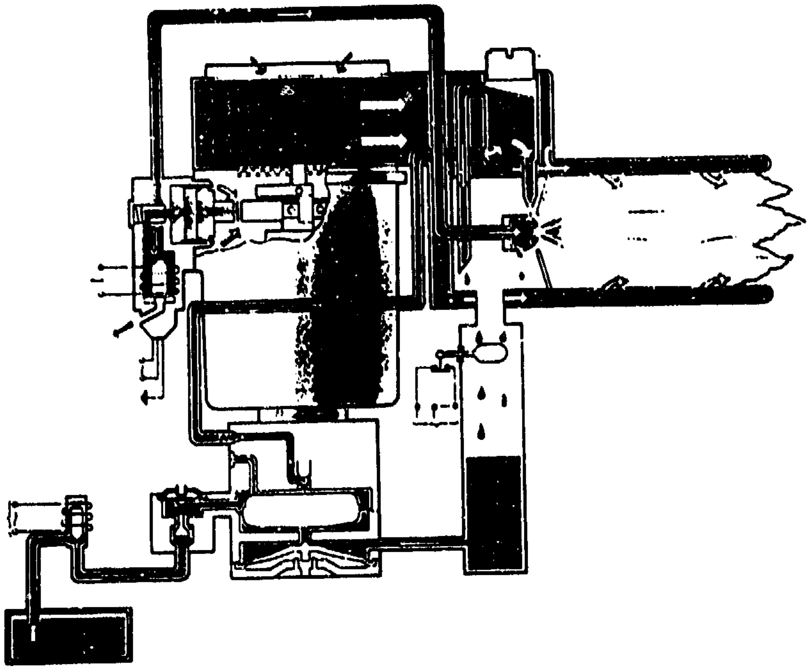


Figure 5.2 Schematic of Babbington Burner

The combustion efficiency of the Babbington burner is reported to be very high (<98%) because of the almost uniform distribution of very fine liquid particles. Other types of nozzles will usually form liquid particles with a broad normal distribution of particle size, so that there are always a few large particles which do not burn completely. These large particles can lead to incomplete combustion.

The Babbington burner was developed under funding from Brookhaven National Laboratory. It is currently being commercially produced for the home heating market in Europe through a license agreement with Babbington under the "Airtronic" name.

The Babbington burner does have several drawbacks. It has been reported to be orientation sensitive and it also requires recirculation of the fuel. The orientation sensitivity may not be a problem in a stationary commercial burner, however, it could definitely pose problems in a portable generator for the armed forces which would not necessarily always be operated on level surface.

In the 1984-85 time period, a burner was developed for the Army by General Atomic Company for the 1500 watt thermoelectric generator that GA was developing under contract to Ft. Monmouth. The fuel and ignition assembly for this burner, shown in Figure 5.3, used a standard home furnace Monarch oil burner nozzle which operated at 40 p.s.i.g. of fuel pressure. The burner worked very well for the period of time that it was under test, however, it was only run for a few hundred hours, which was not enough to obtain any meaningful statistics on its operation. It worked considerably better than the ultrasonic nozzle that was used on the program previously. Details of this development are reported in Reference 5.1. A schematic of the fuel system used for GA's 1.5 kW generator is shown in Figure 5.4. This system is very dependant on good fuel filtration because of the small orifices used in the Monarch type nozzle that provides the fuel atomization.

During phase 1 of the Coast Guard 1.5 kW generator program, Hi-Z recommended the use of the Babbington burner. It was thought that orientation of the nozzle in that situation would not be a major problem in the Major ATON system because the generator would be used in an installation where there would be a firm level footing. However, prior to receiving the phase II award to build the 1.5 kW generator it became difficult to work with Babbington because they were working with another thermoelectric group and perceived a possible conflict of interest.

Hi-Z set out to develop its own nozzle design. After considering the alternatives, we came up with the concept of the aspirated wick nozzle. This nozzle is significantly different than the Babbington nozzle and overcomes some of the problems thought to be inherent in the Babbington design.

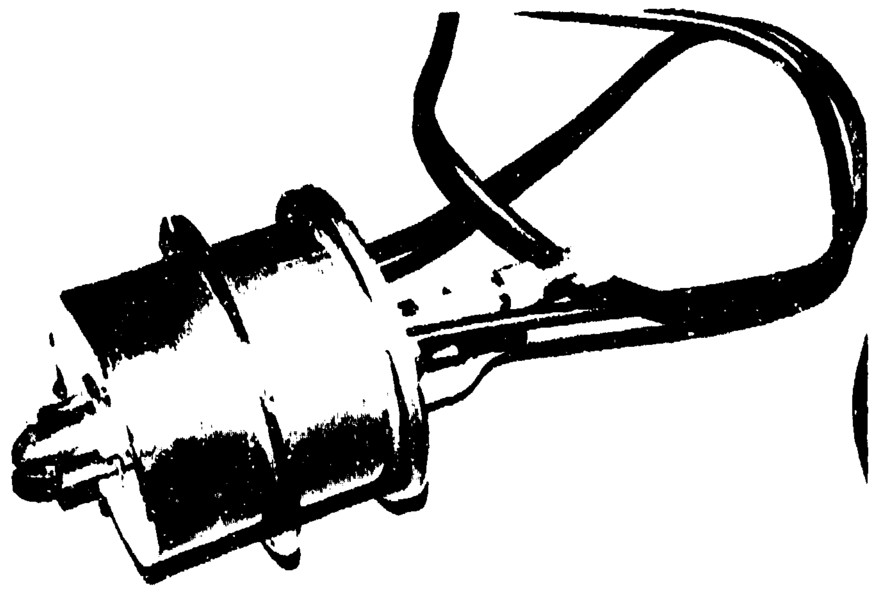


Figure 5.3 Fuel Nozzle and Ignitor Electrode Assembly for General Atomic's 1.5 kW Generator Burner

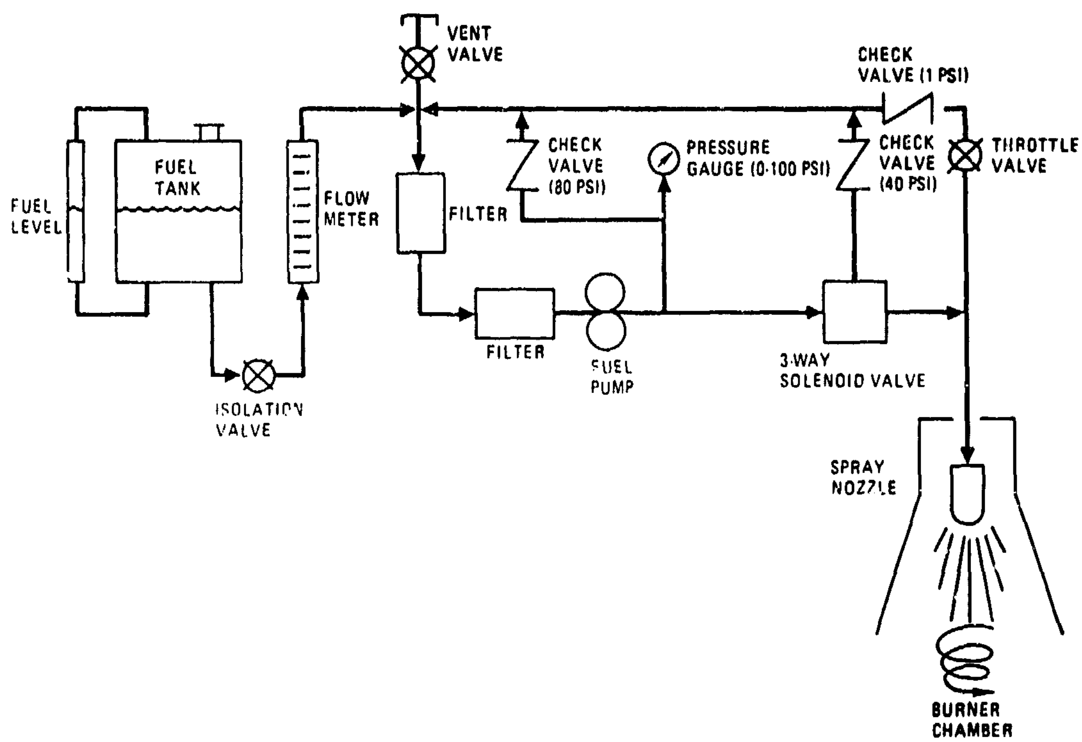


Figure 5.4 Schematic of Fuel System for GA's 1.5 kW Generator

The aspirated wick nozzle is shown in Figure 5.5. It consists of a cylinder which is flat on both ends. Air is introduced into the rear center of the nozzle at between 3 and 5 psi and exits through a small hole in the front center of the nozzle. Fuel is introduced along the top side at essentially no pressure and flows unrestricted through a relatively large opening and exits the front of the nozzle into an open mesh metal screen. Capillary force of the liquid between the screen and the nozzle surface draws the liquid out across the surface. Surface tension also causes the liquid to form into a thin film between the openings in the screen including the area around the air exit. Air exiting through an opening in the screen breaks the liquid film into fine droplets and entrains them in the exiting air stream.

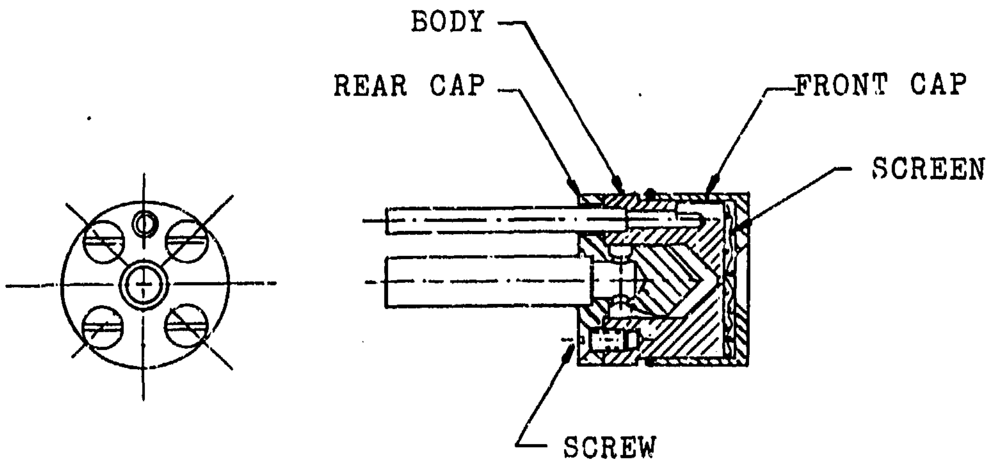


Figure 5.5 Layout of Aspirated Wick Nozzle

The liquid only exits with the air stream. As it leaves the surface capillary action and surface tension replaces the removed liquid and is in turn atomized into fine droplets.

Some of the perceived advantages of the air aspirated wick nozzle are:

- The fuel atomization rate is controlled by the fuel rate to the nozzle
- The size of the droplets formed is directly proportional to the fuel flow, i.e. the lower the flow, the finer the atomization.
- No return fuel flow is required.

- The nozzle is not sensitive to orientation. The nozzles tested ran unchanged when placed at least ±45° from their normal orientation. It is believed that, if necessary, they can be designed to operate in the completely inverted position if a fine wire screen wick is used.

Bench test of the air aspirated wick nozzle were run during the Coast Guard's 1.5 kW program during which the nozzle was operated at liquid flow rates up to 1.4 gallons per hour. The quality of the atomized spray leaving the nozzle compares favorably with that of a high pressure nozzle. The liquid flow rate can be turned all the way down with the droplet particle size decreasing as the flow rate trends toward zero.

Hi-Z has applied for a patent on the air aspirated wick nozzle. We feel that it will provide a good fuel nozzle in both thermoelectric and non-thermoelectric burner applications and we recommend its use in the burner for the 500 Watt thermoelectric generator.

6.0 Fuel Pumps

The fuel pump for the 500 Watt generators needs to supply 0.5 gallons of fuel per hour at a pressure of about 1 psi. The pressure requirement is set by a relief check valve in the fuel line which is set at the 1 psi to terminate fuel flow when the fuel pump is stopped. This check valve action prevents fuel resident in the line between the fuel pump and the fuel nozzle from continuing to flow slowly into nozzle when the pump is shut off.

Hi-Z investigated four commercially available fuel pumps which can provide the low fuel flow rates for the 500 Watt generator application. Three pumps are gear type pumps and the fourth is a valveless piston pump.

6.1 Gear Pumps

The gear pump uses two engaged spur gears to carry the fuel from the inlet to the outlet. This type of pump, in larger volume versions has been used in various forms for hydraulic service for some years.

The Graylor Company makes a small brushless D.C. motor driven gear pump, shown in Figure 6.1 which is low cost, lightweight and low volume. The motor for this pump is a brush type which would have to be replaced with a brushless motor to have any hope of achieving the reliability level required for the 500 Watt generator.

The cost of the Graylor pump is low enough even with the added cost of a brushless motor that it may be worth the effort to determine its reliability by multiple tests. These tests would have to include cold weather because of Graylor's plastic case. Hi-Z used the Graylor pump to test the aspirated wick nozzle during its development and it worked well in that application for the short period of time required.

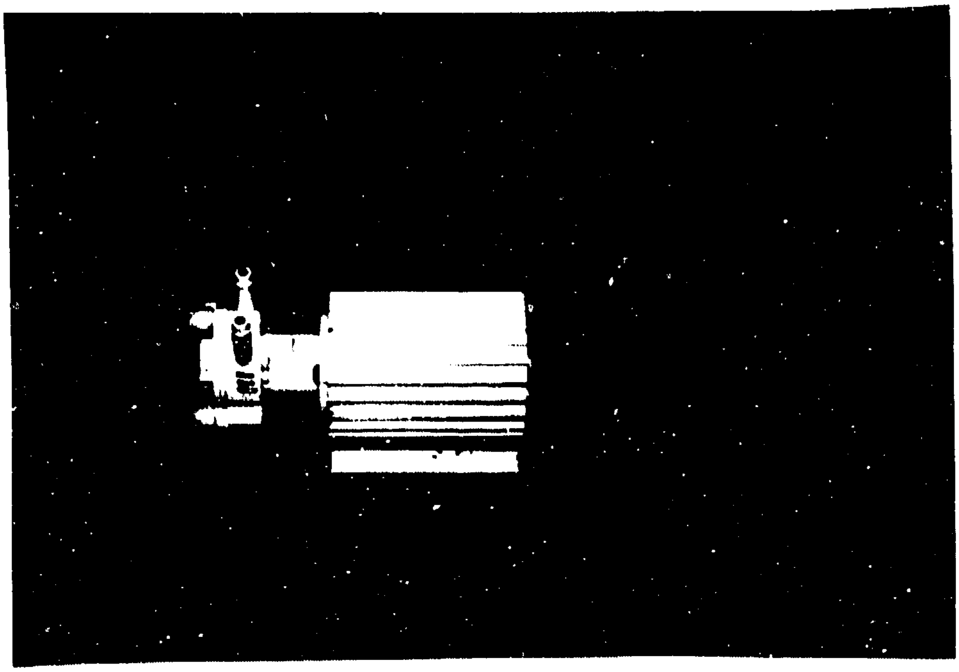


Figure 6.1 Graylor Gear Type Fuel Pump

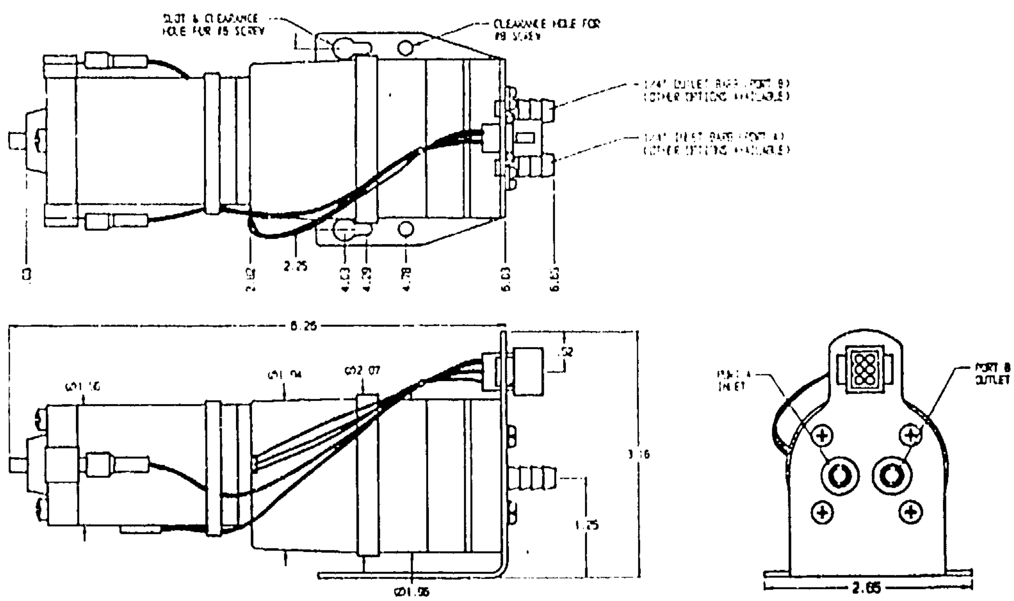


Figure 6.2 Xolox Gear Type Fuel Pump

A second gear pump considered for the 500 watt generator application was the moderately priced series 1000 "Picopump" made by the Xolox Corporation shown in Figure 6.2. This pump is similar in concept to the Graylor pump but includes a speed reducer between the brush type DC motor and the pump. As with the Graylor pump, there is a shaft seal between the pump and the motor which could be a source of reliability problems.

A graph of pressure vs flow rate for the Xolox pump is shown in Figure 6.3. This shows that the pump would supply the required fuel output at about 13 volts.

Xolox plans to introduce a new pump to the market in the fall of 1994. This pump is reported to include a brushless D.C. motor and a sealless magnetic coupling similar to the one used by Micropump which will be discussed later. The price for the new pump will place it in the expensive category, but its MTBF should be in the 20,000 hour range in the 500 Watt generator application.

Micropump shown in Figure 6.4 provides what could be considered the "Cadillac" of fuel pumps. We believe they originated the sealless magnetically coupled, low flow fuel pump. The problem is that this pump is "over designed" for the 500 Watt application since it is designed for pumping small volumes of fluid at up to 100 psi. The unit is made of stainless steel which increases the weight and cost of the pump considerably.

The brushless DC motor use on the model LG-184 Micropump is really a canned rotor DC stepping motor. The electromagnetic field coils, which are placed around the outside of the end of the pump, are switched at the rate desired to produce a given pump R P M. This switching rate is varied by a 0 to 5 Volt input signal.

The magnetic lines of force from the coils is transmitted through the walls of a non-magnetic can which surrounds the magnet which is attached to the pump shaft. Since the shaft is inside of the can, no shaft seal is required. The remaining gasket seals are all static.

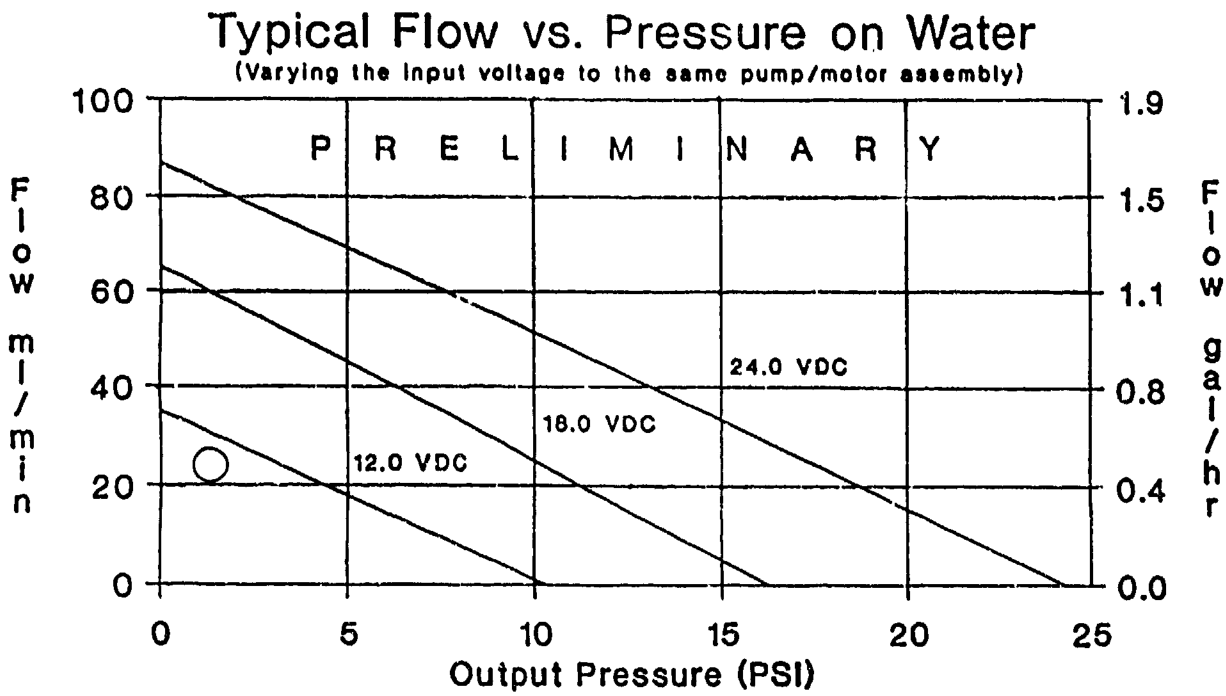


Figure 6.3 Pressure Vs Flow Rate for Xolox Pump

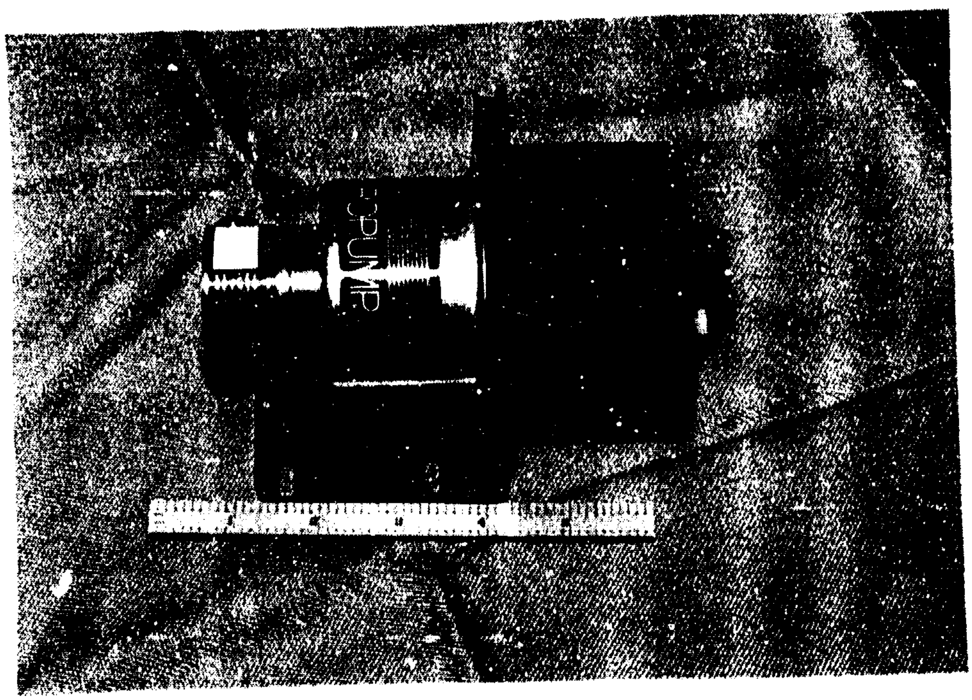


Figure 6.4 Micropump Gear Type Fuel Pump

The MTBF of the Micropump is established for 100 psi operation at 5,000 hours. It is felt that the MTBF should be at least 20,000 hours if the pressure is reduced from their nominal 100 psi rating to the 1 psi required for the 500 Watt generator.

6.2 Valveless Piston Pump

The valveless piston pump is manufactured by Fluid Metering, Inc., (F.M.I) is shown in Figure 6.5. The valveless piston pumping function is accomplished by the synchronous rotation and reciprocation of the piston in the precisely mated cylinder bore. One pressure and one suction stroke are completed per cycle. A duct (flat portion) on the piston connects the cylinder ports alternately with the pumping chamber, i.e., one port on the pressure portion of the pumping cycle and the other on the suction cycle. The mechanically precise, free of random closure variation valving is performed by the piston duct motion as shown in Figure 6.6.

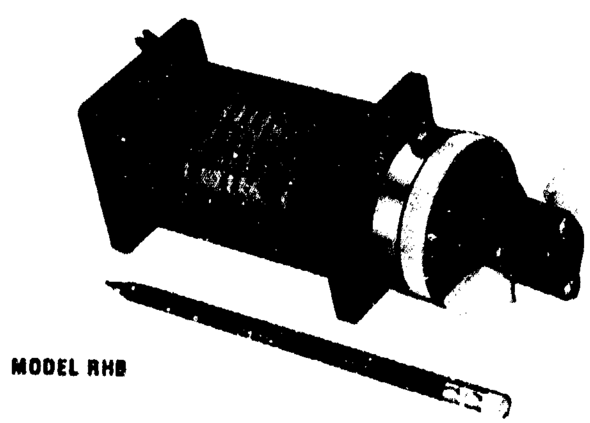


Figure 6.5 FMI Valveless Piston Pump

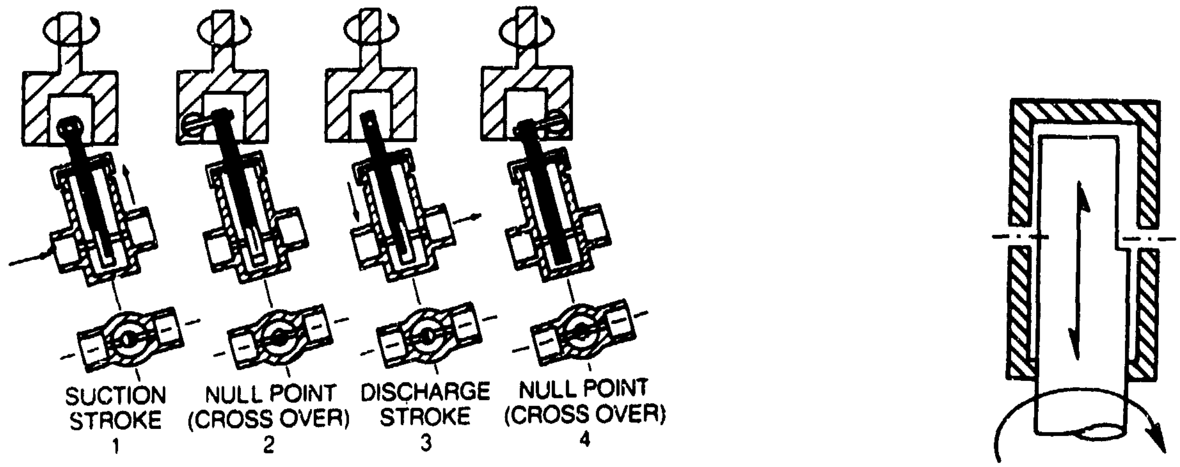


Figure 6.6 Operation of Valveless Pump

The pump head module containing the piston and cylinder is mounted in a manner that permits it to be swiveled angularly with respect to the rotating drive member. The degree of angle controls stroke length and in turn flow rate. The direction of the angle controls flow direction. The reciprocation accuracy and positive valving of FMI pumps provide exceptional performance and dependability.

In the thermoelectric generator burner fuel pump application, the angle between the valveless piston pump head and the drive will be fixed to deliver the desired flow rate for the burner. Variations in the volume delivered to control the burner heat output and compensate for both altitude and fuel changes will be obtained through variations in the drive motor speed. The moderately priced FMI STH pump with a brushless DC motor running at about 2000 RPM would deliver the 0.5 gallons/hr fuel required.

There are several questions that remain about the valveless piston pump. First, while the pump is perceived to be reliable the company, which has been building these pumps for about 35 years, does not have any actual reliability statistics. The second problem is that the output flow is a pulse and not a steady flow such as would be most preferred for optimum burner operation. However, since the pulses are at a rate of about 60Hz, they may be easy to dampen.

The potential advantages of the valveless piston pump are low volume, lightweight, and low power drain and moderate cost.

6.3 Solenoid Pumps

There are several solenoid type pumps that could work for the 500 Watt application. These pumps are typically low efficiency devices compared to motor driven pumps. They also deliver their fuel in a pulsed mode which is at a much lower frequency than FMI's pump and therefore is more difficult to dampen. In addition, the solenoid type pump typically have a lower reliability than rotary types of pumps. As a result, we do not consider solenoid pump applicable to the 500 Watt generator program.

6.4 Pump Recommendation

At the present time we are recommending the Micropump for the 500 Watt because it appears that it will fulfill the requirements of the generator without difficulty. We also recommend that we test both the FMI valveless piston and the Xolox "Picopump" to confirm their reliability with the intent to change pumps to save both cost and weight should either prove to have the MTBF required for the 500 Watt Generator.

7.0 Blowers, Fans and Pumps

The 500 Watt thermoelectric generator requires a combustion blower to supply air to the burner, one fan to provide cooling air to the heat sink and an air pump to provide air to the fuel nozzle. All three of these units will incorporate brushless DC motors for high efficiency and high reliability.

7.1 Combustion Blower

Combustion air is supplied to the burner by a centrifugal fan. The heat combustion and heat balance calculations for the 500 Watt generator show that the 38.4 cfm is the air flow rate required for this system operating without a recuperator.

The model TBK - 2.5 blower shown in Figure 7.1 manufactured by Brailesford and Co. will fulfill the blower requirements. This blower is one of the most compact of the several blowers considered for this application. The curve of pressure vs. flow rate for the TBL- 2.5 which has the same dimensions as the TBK - 2.5, is shown in Figure 7.2 and the power consumption curve is shown in Figure 7.3.

7.2 Cooling Fan

The fan selected to provide the air for the heat sink is produced by Papst-Motoren GmbH and Co. It is a Model 2248 vane-axial fan with a maximum free air flow rate of 353 cfm shown in Figure 7.4. The fan draws 32 watts at maximum power. The air cooling fan for the 500 Watt generator will be operated at a flow rate between 250 and 300 cfm. The performance characteristic curve for the 2248 is shown in Figure 7.5.

Papst is currently manufacturing this fan only for a nominal 48 Volts DC operation. However, Papst says that will introduce a nominal 24 Volt DC version with the same performance during 1994.

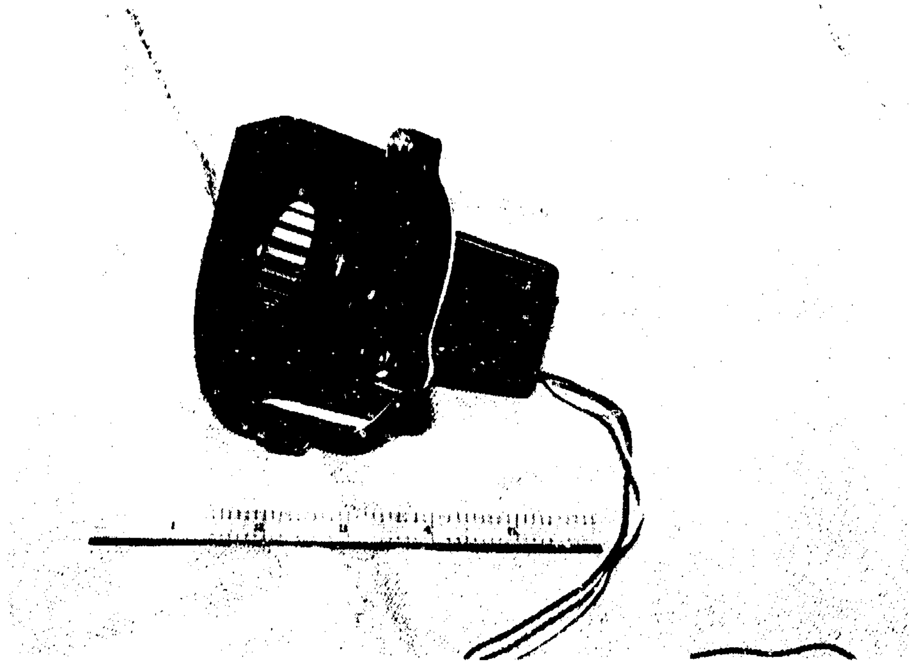


Figure 7.1 Brailesford TBK - 2.5 Centrifugal Combustion Blower

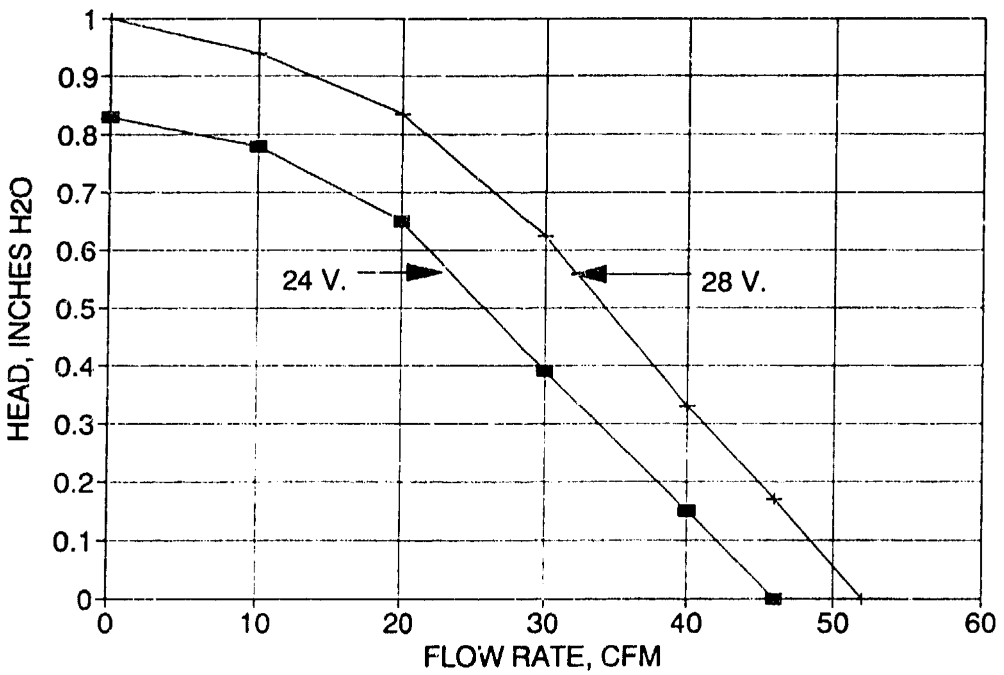


Figure 7.2 Head vs Flow Rate for TBK - 2.5

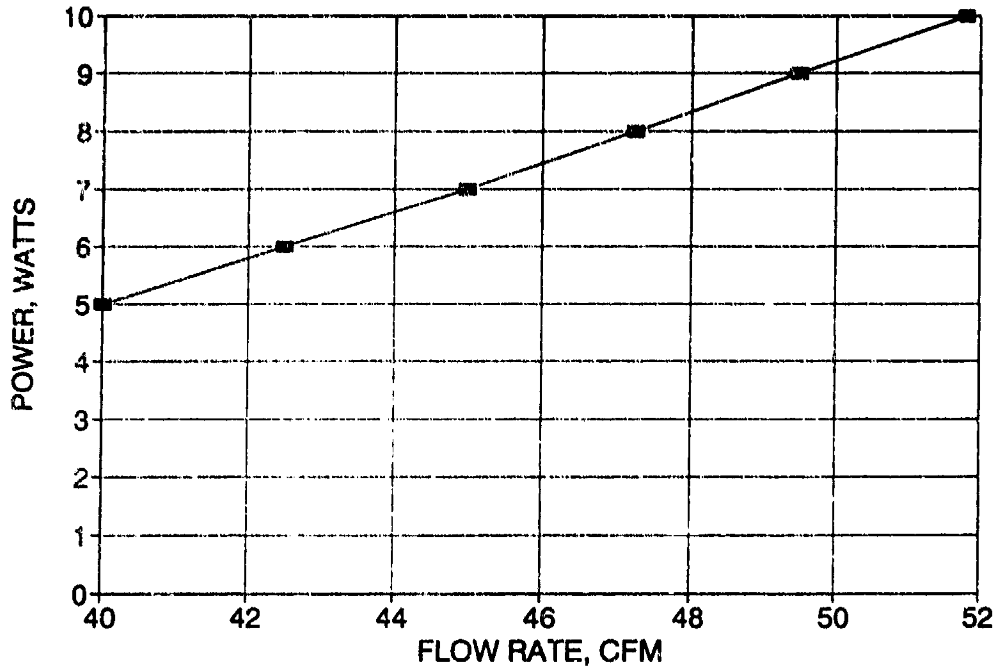


Figure 7.3 Power vs Flow Rate for TBL-2.5

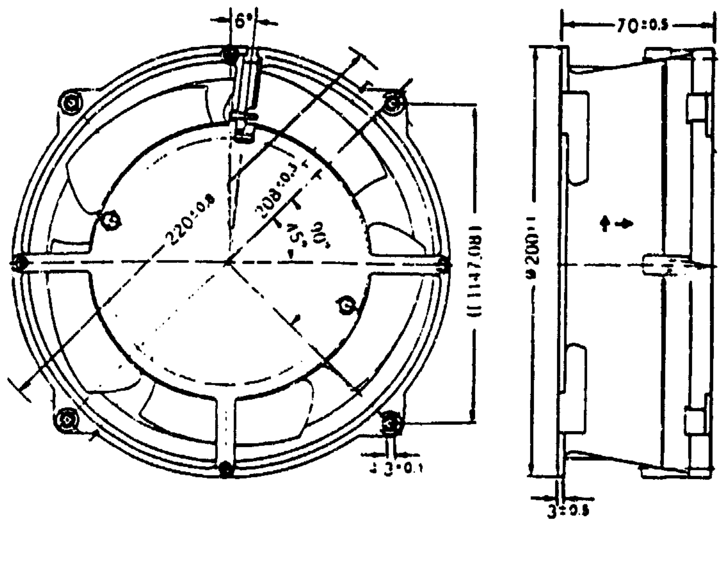


Figure 7.4 Outline of Papst 2248 Fan

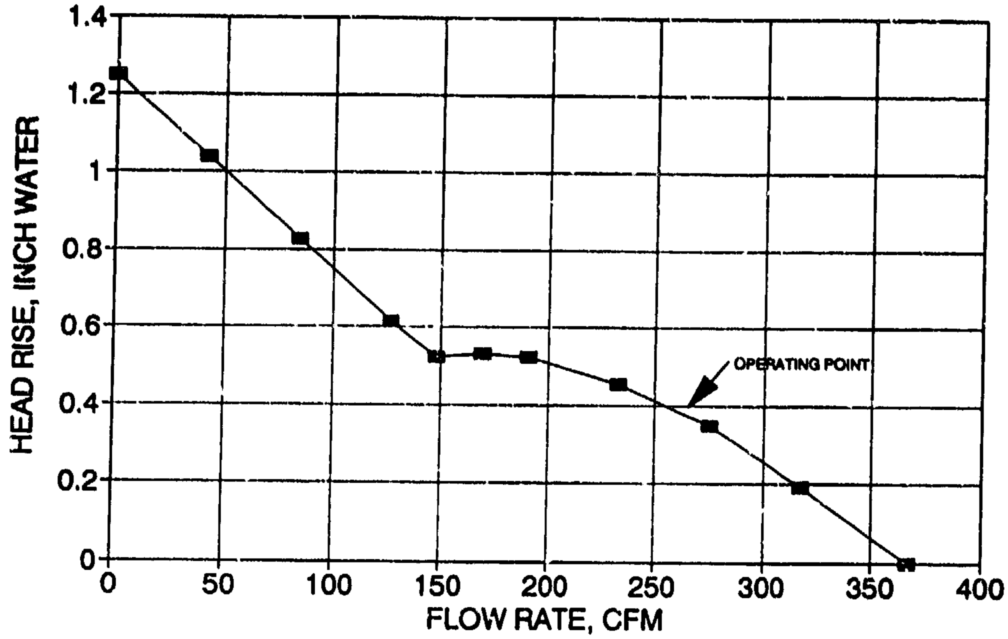


Figure 7. 5 Head Rise Vs Flow Rate for Papst 2248 Fan

The Papst fan has an MTBF at 40°C of 80,000 hours. The sound pressure in free air is 57 dB under maximum operating conditions.

7.3 Air Pump

The aspirated wick fuel nozzle will require a flow rate of about 14 liters of air per minute at 5 psi. This air will be provided by an oilless sliding vane type air pump produced by Gast Corporation. Gast custom built a demonstration unit of this pump which was driven by a nominal 28V brushless DC motor for the 1.5 kW Coast Guard program. The pump operated in accordance with the requirements of that program and can also be used for the 500W generator design.

8.0 Inverter

The 500 Watt generator is required to provide its output at 110V at 60 cycle AC. This necessitates an inverter because the basic output of the generator is DC.

There are a large number of 500 Watt inverters on the market. They are used in a large number of applications and their prices vary over quite a wide range. Most of the inverters available on the market are reasonably large, heavy, and do not advertise their expected MTBF since these factors are not of major importance in most commercial applications.

The inverter selected for the 500 Watt generator is manufactured by KGS Electronics, Inc. The KGS model S550 is a solid state DC to AC static inverter that inverts a nominal 28V DC to 115V AC 60 Hz sinusoidal voltage. The total continuous output power rating of 500VA. The model S550 is designed to meet Federal Aviation Administration (FAA) Technical Standard order TSO-C73 for airborne static electric inverters.

The specifications for the S550 inverter are shown in Table 8.1. An outline drawing is shown in Fig 8.1.

It should be noted in Table 8.1 that the weight of the S550 is only 4.3 lb. This is much lower than other comparable units by up to a factor of 6 or 7. The model S550 has an advertised MTBF of 10,000 hours, which creates a problem in achieving the goal of 10,000 hrs MTBF.

Table 8.1 Specifications for KGS S550 Inverter

INPUT VOLTAGE:	21 to 36 Vdc (28 Vdc nominal)
INPUT CURRENT:	22 Adc at Full Load (nominal) 0.5 Adc at No Load
OUTPUT VOLTAGE:	116 Vac ± 2 Vac (nominal)
OUTPUT CURRENT:	4.3 Aac at Full Load (nominal)
OUTPUT POWER:	500 VA Total (continuous)
OUTPUT FREQUENCY:	60 Hz ± 0.5 Hz
PHASE & WAVEFORM:	Single-phase, sinusoidal
HARMONIC DISTORTION:	1.5% (nominal)
EFFICIENCY:	83% (nominal)
REGULATION:	1% Line, 1% Load, 1% Temperature
OVERLOAD CAPACITY:	110% of the rated output power for a period of two (2) hours; 125% of the rated output power for a period of 5 minutes (minimum).
PROTECTION CIRCUITS:	The inverter will shutdown under the following conditions: Input voltage > 36 Vdc. Input voltage < 20.5 Vdc. Internal high ambient temperature. Short circuit condition. The inverter is protected in the event of an input reverse polarity connection.
REMOTE ON/OFF:	Yes
OPERATING TEMPERATURE:	-55°C to 71°C (-65°F to 160°F)
ALTITUDE:	55,000 Ft.
SIZE:	9.50"L X 6.19"W X 3.38"H (Mounting Flange Included)
WEIGHT:	4.3 lb. (1.95 kg)
MATING PLUG:	MS-3106A18-9S

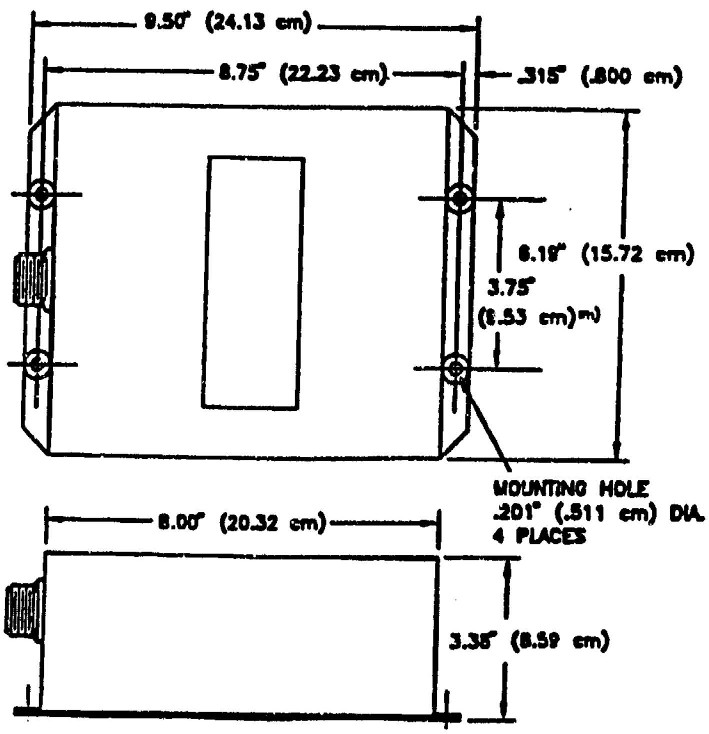


Figure 8.1 Outline of KGS S550 Inverter

9.0 Power Conversion Unit Description

The layout of the power conversion unit (PCU) is shown in Figure 9.1. Combustion air enters the combustion chamber through the small centrifugal blower from the top side. The air inlet to the burner is placed to one side of the chamber to introduce swirl air flow.

Atomizer air is introduced to the air aspirated fuel nozzle on the centerline of the PCU behind the cooling fan. The fuel line enters the rear of the combustion chamber at a point just above the atomizer nozzle and then turns and enters the side of the nozzle.

The nozzle sprays atomized fuel through a hole in the center of the rear of the flame holder. Initial combustion occurs when the air/fuel mixture is ignited by the high voltage spark formed between the two ignition electrodes which enter the bottom side of the combustion chamber.

Some of the swirling combustion air enters the rear of the flame holder to form an easily combusted stoichiometric air fuel ratio. The remainder of the air flows outside of the flame holder and enters the combustion area radially through holes in the side of combustion chamber. This secondary air cools the flame to achieve the desired combustion temperature.

Combustion continues as the swirling gasses move down the flame tube. The swirling flow action tends to send the dense cooler gasses to the outside and the lighter hot gasses to the inside of the vortex that is formed. The hot gasses which are at a temperature above the auto-ignition temperature of the fuel return along the centerline of the burner toward the nozzle where they reignite the new air fuel mixture. This vortex action stabilizes the combustion so that the ignition spark is no longer required to maintain combustion.

The combustion gasses exit the end of the flame tube and reverse their course flow between the outer surface of the flame tube and the inner surface of the module support structure. Fins are cast into the inner surface of the support structure to provide additional heat transfer area. The gas

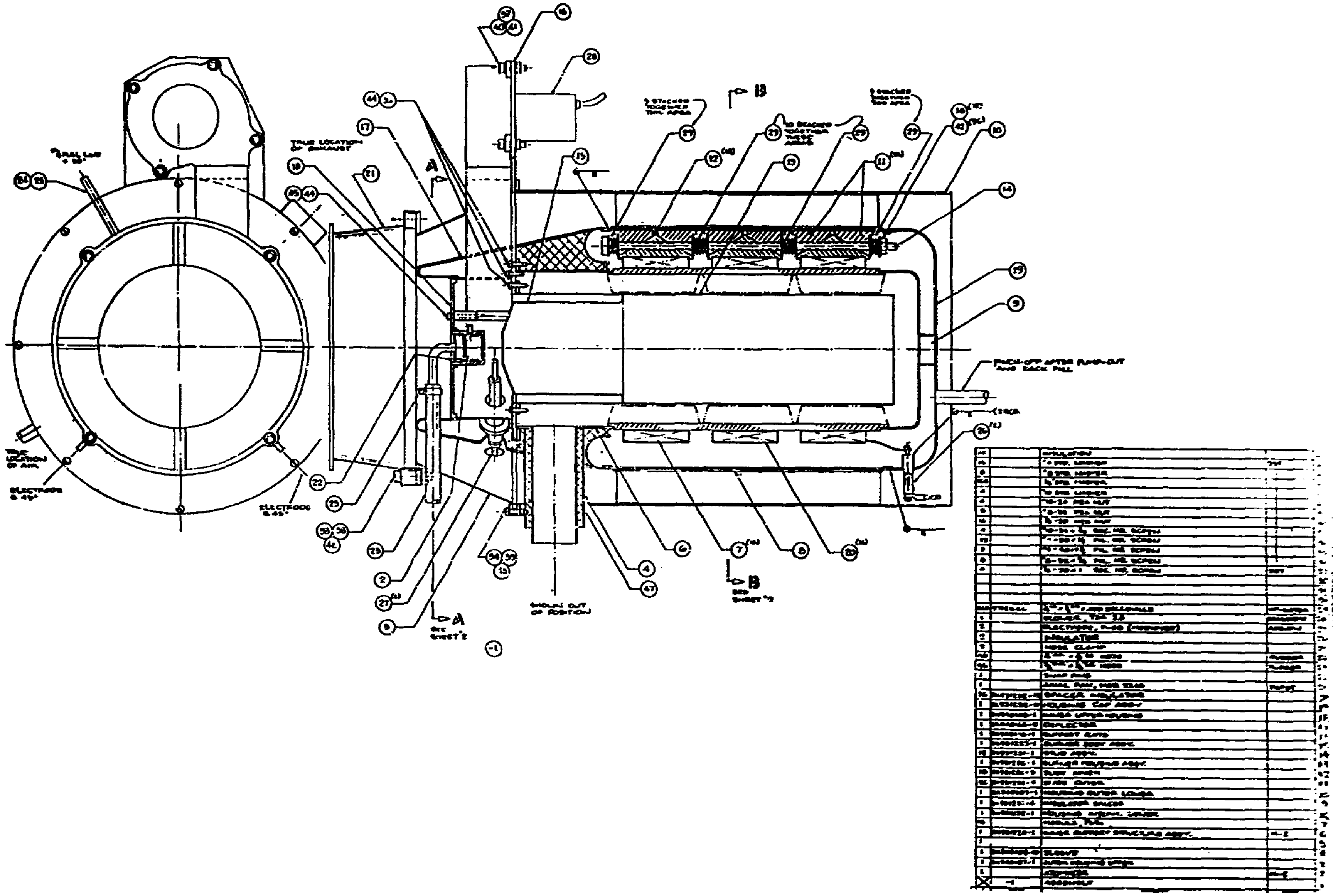


Figure 9.1 Layout of 500W Power Conversion Unit

temperature drops considerably as the combustion gasses loose energy to the support structure and cool, three separate sets of fins with different number of fins in each set are used to flatten the temperature distribution along the support structure. The combustion gasses then exit the region of the support structure and pass to the exhaust chamber and out through the exhaust tube in the bottom side of the PCU. The module support structure which will be made of an investment casting of high temperature alloy is circular in the center with a hexagonal surface on the outside.

A layer of copper will be plasma sprayed on the outside of the machined surface of the support structure to improve heat transfer to the thermoelectric modules.

Three thermoelectric modules (see Section 11) are placed uniformly along each of the six flats of the support structure with a 0.01 inch thick piece of aluminuna electrically isolating each module from the metallic support structure. The modules are pressed against the support structure with a pressure of about 200 psi by spring loaded systems of aluminum wedge blocks. Each of these wedge block sets are compressed by Bellville springs which act along a line parallel to the center line of the support structure. The compression force of the springs causes the sets of blocks to expand radially to fill the gap between the cold side of the module and the inner surface of the heat sink structure. Waste heat is thus transferred from the module to the heat sink. In addition, the sliding action of the wedge blocks accommodate the thermal expansion differences which occur between the hot support structure and the cooler heat sink structure.

The sliding surface of the aluminum wedge block will be coated with the SynTek's SymCoat EMT. This coating process applies a hard coating of electroless nickel on the surface of the aluminum which is subsequently impregnated with Teflon. This coating will provide a hard, permanently lubricated surface, with a low coefficient of friction, and low thermal contact resistance between the surfaces.

The heat sink structure is a composite cylinder of stainless steel and aluminum. A thin layer of stainless steel will be on the inside with aluminum on the outside. Radial aluminum heat transfer fins will be brazed onto the outer aluminum surface for heat transfer to the air. The heat flux on the cold side of the generator varies from 0.15 to 0.17 Watts/cm^2 based on the fin area.

A thin stainless steel omega ring is welded between the exhaust end of the module support structure on the stainless steel portion of the heat sink structure. This flexible ring provides a leak tight seal between the two structures and also allows differential thermal expansion between the hot support structure and the cooler heat sink structure. The other end of the annular region which contains the modules is sealed by a circular cap welded at the end of the heat sink structure. A piece of foamed silicon carbide material is placed in the center between the two end caps to minimize flexing of the out cap when the interior of an annular volume is evacuated, prior to back filling with inert argon gas. The evacuation and back fill operation are conducted using a pinch off tube (shown as a plain tube on the drawing) welded into the outer end cover. The tube will be covered with a protective cap following the pinch off and welding procedure. The interior space between the modules and the end caps will be filled with high temperature fibrous insulation to minimize heat leaks and maximize efficiency.

The outer shell around the heat sink and burner will be made of a light weight composite plastic material. This shell is shaped to guide air flow from the cooling fan which is mounted on one end, by the burner chamber and over the heat sink fins with minimum pressure loss. The cooling fan will be bolted directly to the containment cover.

The power leads from the modules pass through two hermetic feedtroughs welded into the heat sink structure. Access to these leads is through the outlet end of the heat sink.

10.0 System Thermodynamic Analysis

A code cal HBALANCE written by Hi-Z was used to analyze the thermodynamics of a thermoelectric system which uses a liquid fuel as its heat source. The code is based on the system shown schematically in Figure 10.1 which includes a burner, the thermoelectric modules, a recuperator, the necessary blowers and pumps for both combustion and for heat sink cooling.

The combustion equation in the model use dodecane ($C_{12}H_{26}$) as the chemical model for Diesel fuel. Diesel fuel, like gasoline, is a mixture of a large number of different chemical fractions and is very difficult to treat exactly. The stoichiometric dodecane reaction is given by:

$$C_{12}H_{26} + 18.5(O_2 + 3.8N_2) \rightarrow 12CO_2 + 13\ H_2O + 70.3N_2$$

The capability of handling excess air is also included in the model to obtain the combustion temperature desired.

A recuperator was included in the system so that the effect of exhaust energy recuperation on fuel consumption could be determined. A recuperator will not be specifically designed into the 500 Watt generator since the design criteria includes minimum weight and minimum volume and not minimum fuel consumption.

The heat balance model is run by selecting various temperatures required throughout the system and by using various thermoelectric conversion efficiencies. These conversion efficiencies are calculated by a separate thermoelectric code (THEAT) written specifically for that purpose.

Figure 10.2 presents the variation in system fuel rate and exhaust temperature as a function of recuperator effectiveness over the range of 0 to 60% effectiveness in a system with the maximum combustion temperature fixed at 1100°C, the temperature of the combustion gas leaving the module area is 700°C and the actual module conversion efficiency is 8.9%. One can see that there is a reasonably large variation in both fuel flow rate and exhaust temperature as the effectiveness of the recuperator is increased.

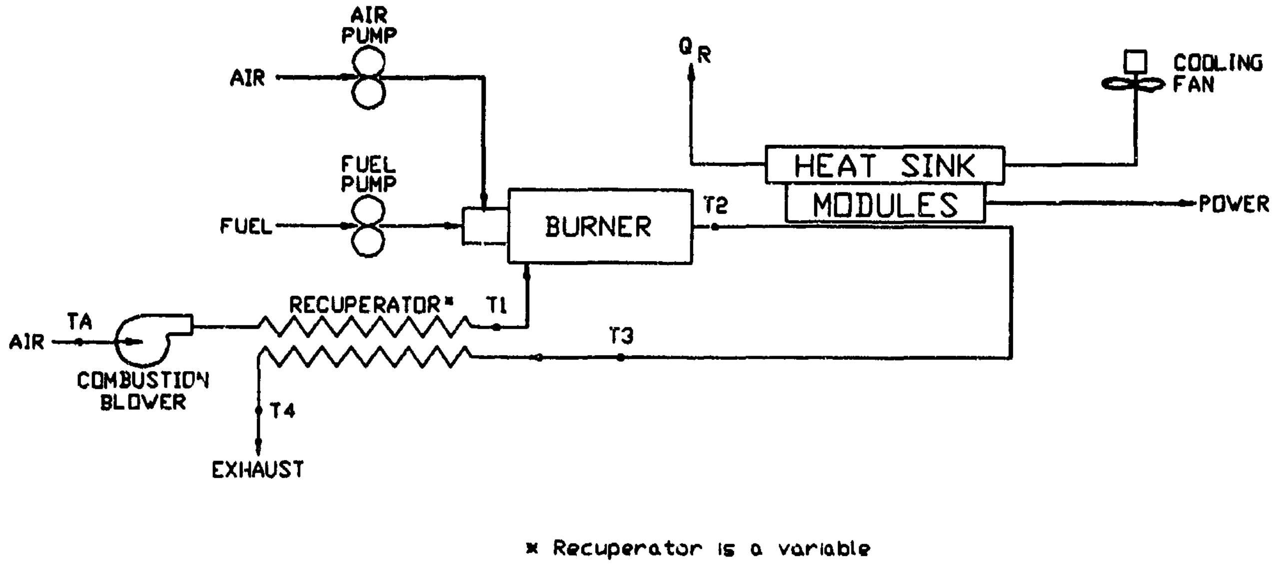


Figure 10.1 System Schematic for Heat Balance Code

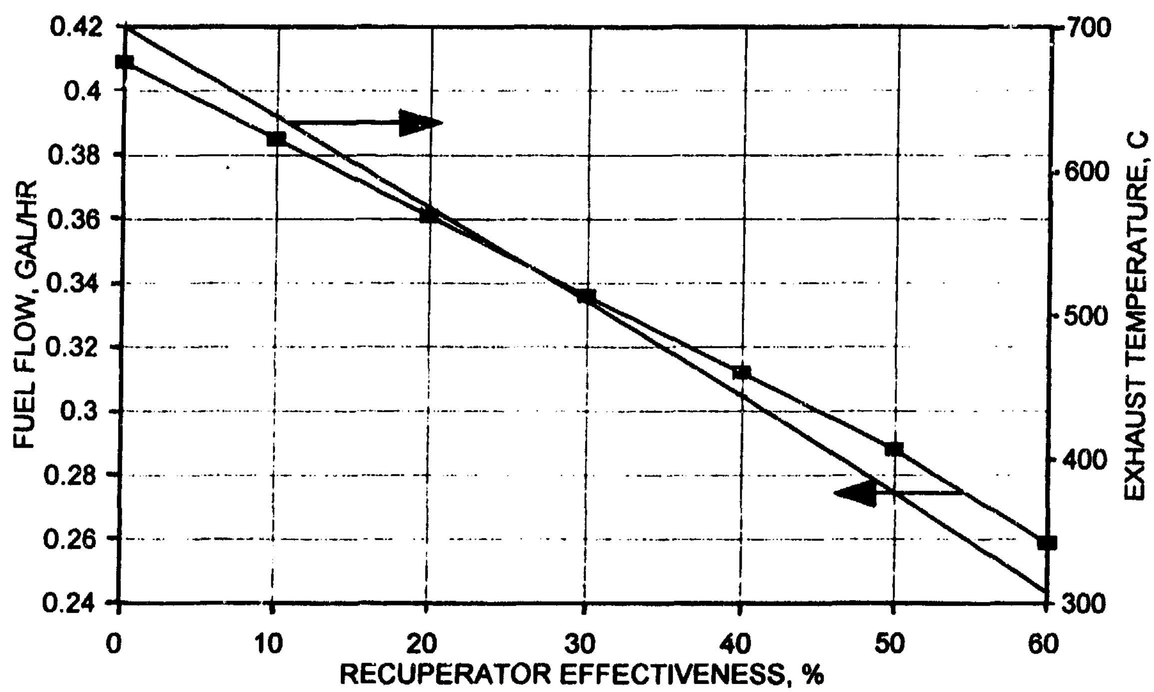


Figure 10.2 Fuel Flow Rate and Exhaust Temperature vs Recuperator Effectiveness for 500W Generator

The set of conditions used to develop the curves in Figure 10.2 represents the conditions expected in the 500 Watt generator cycle. The actual design point would correspond to the zero recuperator efficiency point with a fuel flow rate of about 0.41 gal/hr.

The limitations on recuperator effectiveness that can be used is governed both by the rapid increase in air pumping power required as the effectiveness increases and, in systems which burn sulphur containing fuels such as some grades of Diesel which may contain sulphur, by the condensation point of sulfuric acid (330°C at one atmosphere).

Table 10.1 presents the operating parameters for the 500 Watt generator. This is for a system without any recuperation.

Table 10.1
500W GENERATOR OPERATING PARAMETERS
(No Recuperator)

Module Efficiency, %	8.9
Inlet Temperature, °C	20
Exhaust Temperature,°C	700
Combustion Temperature, °C	1100
Net A/C power, W	500
Net D.C. Power, W	605
Gross Power, W	750

11.0 Thermoelectric Module

Calculation for the thermoelectric module used in the 500 Watt generator were done using a code called THEAT which was written by Hi-Z using the TK SOLVER software.

The module will feature segmented legs for both the N and P legs. This means that there are two materials in each leg which are joined in both thermal and electrical series. Segmentation is done to maximize the electric conversion efficiency of each leg by utilizing the materials which provide the maximum figure of merit over the particular operating temperature range. The segmentation suggested here has been used previously so that it is a proven technology.

The P leg will consist of a segmentation of 3P lead-telluride and P bismuth-telluride. Thirty four percent of the legs length will be P bismuth-telluride.

The N leg will consist of a segmentation of 3N lead-telluride and 2N lead-telluride. The 2N material will form 65% of the total legs length.

The remaining parameters for the module are shown in Table 11.1 below.

Table 11.1 MODULE FOR MINGEN

Material	
P leg	3P PbTe/PBiTe
Segmentation	34% PBiTe
N leg	3N PbTe/2N PbTe
Segmentation	65% 2N PbTe
Element Size	
Width & Depth	0.200 X 0.200 inches
Length	0.226 inches
Number of Couples	49 active
Element Array	10 X 10
Module Thickness	0.325 in
Module Width & Depth	2.1 X 2.1
Hot Junction	555°C
Cold Junction	100°C
Theoretical Efficiency	9.6%
Actual Efficiency	8.9%
Heat Flux	18.85 w/cm^2
Module current	8.35 amp

Terminal voltage	4.889 Volts @ M=1
Module Power	40 Watts
Number required	18
Module Array	3 X 6

The construction of this module which is shown in isometric in Figure 11.1 is similar to the module that was being developed for the 1.5 kW generator program for the U.S. Coast Guard. The development of this module was nearing completion when the Coast Guard could not obtain the contracted funds and its further development was stopped.

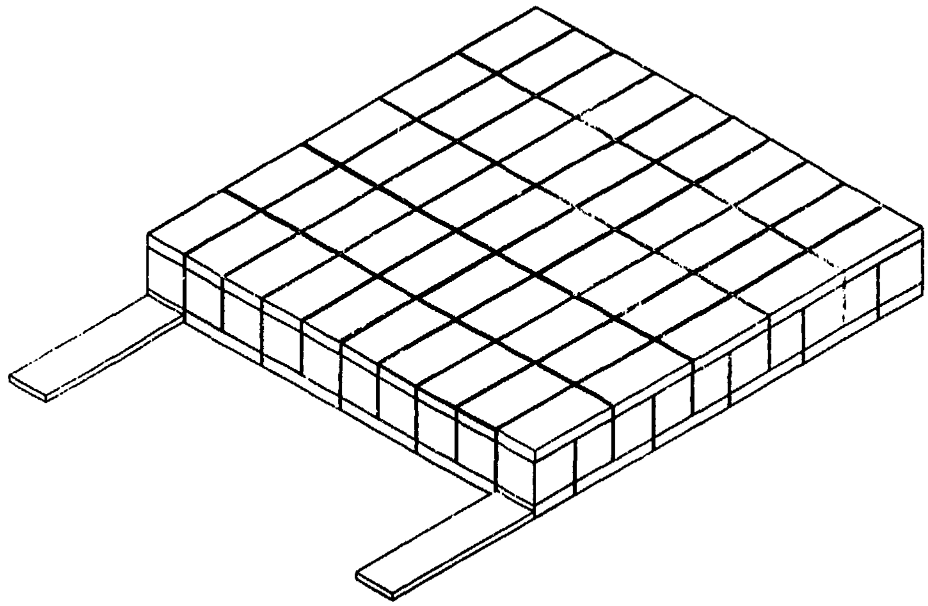


Figure 11.1 40 Watt Bonded Lead Telluride Module isometric

It appeared at the time the program stopped that improved tooling was what was required to complete the bonding process. The tooling we were using in the development of the process did not have sufficient compliance to bond all of the elements at the same time. We believe that only a minor effort will be required to complete development of the bonding process.

The unbonded module developed for the 1.5 kW program was shown in Figure 3.3. This module which can be fabricated by Hi-Z is somewhat more difficult to use because of the need to handle a multiplicity of small parts. In addition, the conversion efficiency is slightly lower because of the increased electrical resistance of the unbonded electrical contacts. We consider this module construction as a backup to the bonded module.

12.0 Control System for the 500W Generator

The objective of the control system for the 500W thermoelectric generator is to provide for the safe startup and shutdown of the system. These functions require a minimum of operator action.

The system shown in block diagram form in Figure 12.1 will have a single on/off switch which will initiate the startup procedure. The system will attempt to start several times before terminating the startup cycle and providing an indication of the cause of the fault. The number of times that the start is attempted is usually set at four, however, this can be changed if desired. When the number of start attempts has been reached, the system will automatically shut down and display a series of indicator lights which should pinpoint the cause for the shutdown.

A reset button will be provided in the control system. It will be necessary to push the reset button to allow the control system to attempt an additional set of start attempts once the system has reached the number of start attempts set as a limit in the control system.

The startup and shutdown safety systems will be based on a timed sequence of actions. Once the signal to start is received, the first action is to reset all systems times. Next the combustion blower and atomization air pump motor or motors are energized.

Ten seconds after the combustion blower has been activated to clear fumes from the combustion chamber, the ignition system is energized. Fifteen seconds after the blower has been activated a signal is sent to the fuel pump inhibit switch. If positive signals are received from both the combustion blower and atomizer air pressure switches, the inhibit switch will be disarmed and the fuel pump will be energized sending fuel to the atomizer.

Verification of fuel flow and combustion must be received within five seconds of energizing the fuel pump or else a signal is sent to the recycle counter which will reset the timers, count one attempted cycle, and attempt a second start.

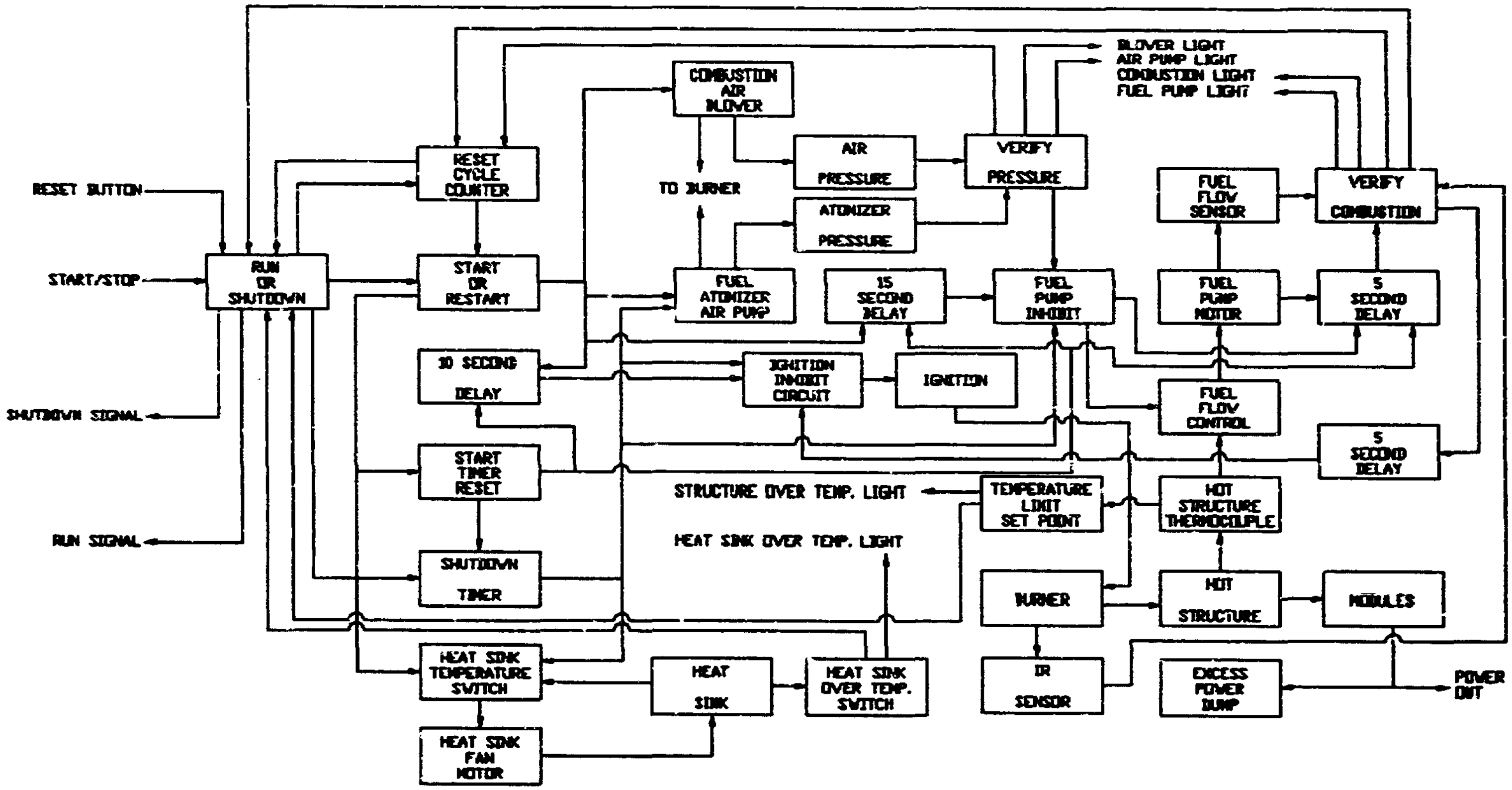


Figure 12.1 500W Generator Control System Block Diagram

If both fuel flow and combustion are verified within the five seconds of initiating fuel flow, a signal is sent to signal the fact the system is operating. Five seconds following combustion verification, a signal will be sent to inhibit the ignition system. The ignition is not required once combustion is established since combustion will be stabilized.

As the temperature starts to rise in the combustion chamber the support structure, the modules, and the heat sink temperature will also increase. The voltage to the fuel pump will remain high until the temperature of the hot structure begins to approach its normal operating temperature (575°C). As the operating temperature is reached, the voltage to the fuel pump will be reduced to its normal value and the fuel flow will be reduced. Should the temperature of the support structure exceed 615°C at any time, a signal will be sent to initiate a shutdown of the system.

The heat sink fan is turned on by an independent thermally activated switch when the heat sink temperature exceeds 75°C. If the temperature of the heat sink exceeds 110°C, a second switch will send a signal to initiate system shutdown.

System shutdown will be initiated either manually by turning the run switch to the "off" position or automatically by a signal indicating adverse or unsafe operating conditions as described above. In either event, the system must be shut down in a safe manner using a shutdown timer which allows the combustion air blower, atomizer air pump, and ignition system to continue to run for an additional thirty seconds following initiation of shutdown.

Any shutdown signal will immediately turn off the fuel pump and start the ignition. The delayed shutdown of the air blower, atomizer pump, and ignition will clear the combustion chamber of any volatile fumes so that the system can be safely restarted.

A single line diagram for the control system is shown in Figure 12.2. The circuit is based on the use of a 68HC705B5FN microprocessor which will be programmed to provide the function required.

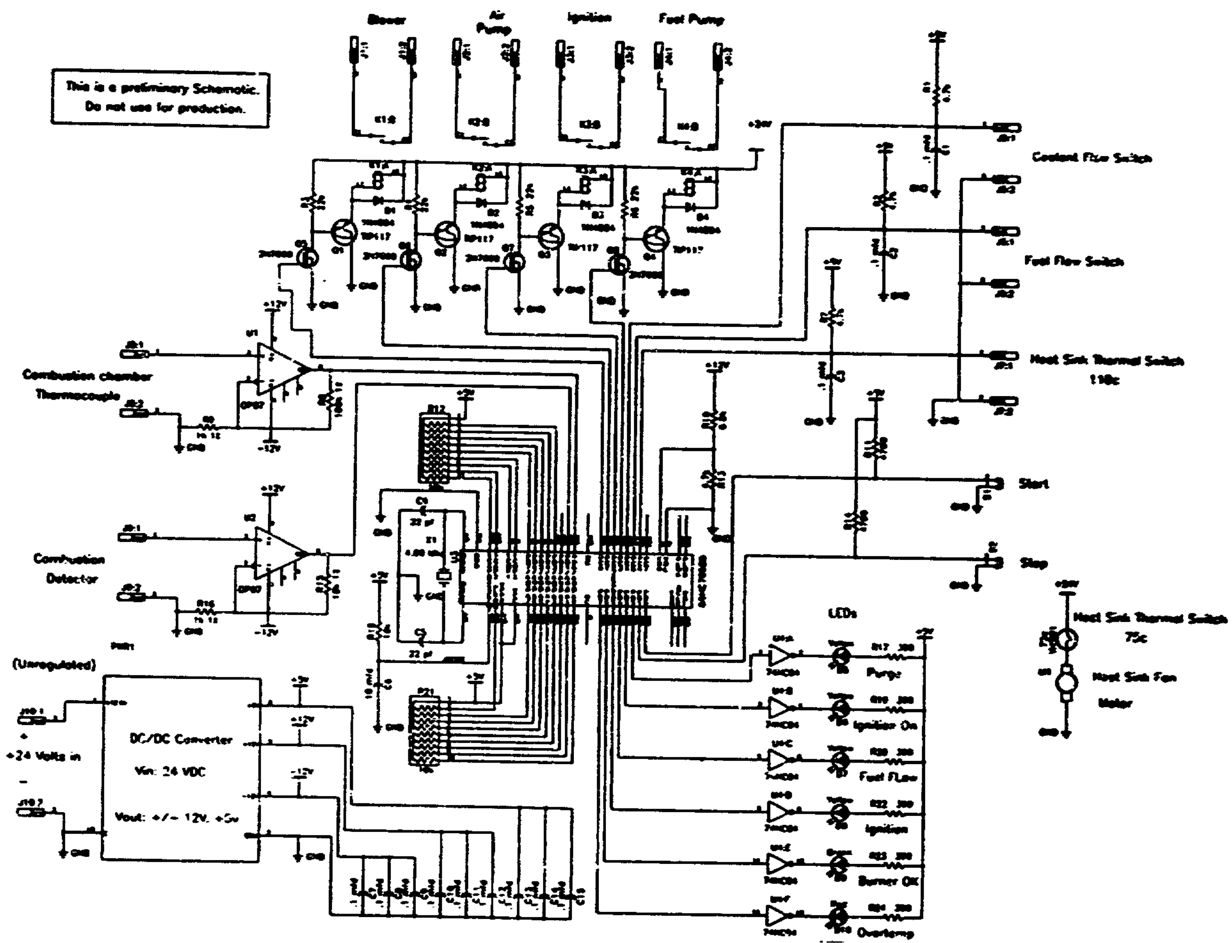


Figure 12.2 Control and Safety System Single Line Diagram for 500W Generator

Thermoelectric generators are usually operated at constant full power. These systems have a reasonably large thermal time constant which makes it difficult for them to respond rapidly to load changes. At lower loads, the excess energy generated will be dissipated in a power dissipator which is shown in Figure 12.3. The power dissipator also includes a battery charging circuit. This circuit is designed so that power is provided to the loads first and then any excess power is used to recharge the battery. The excess electric power dissipated is converted to heat in the resistors and transistors which will be mounted from the cover which surrounds the generator so that the resistors and transistors are positioned in the incoming cooling air stream before it enters the heat sink. This placement will insure that the components will not become over heated and possibly fail as a result.

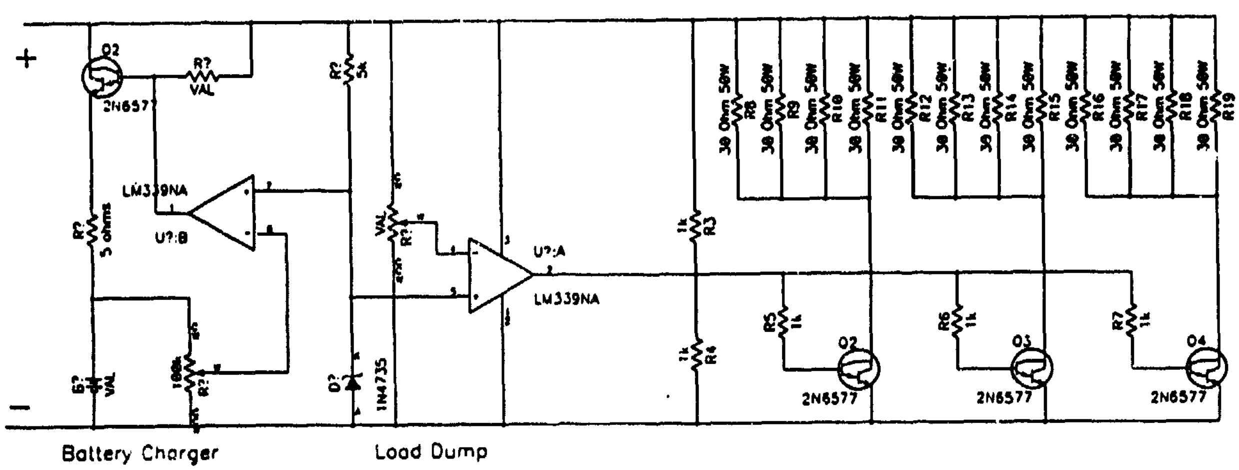


Figure 12.3 Load Dump and Battery Charging Circuit Single Line Diagram for 500W Generator

13.0 System Weight and Size Estimate

13.1 System Weight Estimate

Detailed drawings were made of most of the generator components to accurately estimate the weight of the 500 Watt generator. The weight of each part was then calculated along with the location of the center of gravity of each part within an x - y coordinate system. the origin of the system was selected to be located on the centerline of the PCU at a point coincident with the combustion air blower mounting plate.

A spreadsheet was used to keep track of all weights and the location of their centers of gravity. the spreadsheet then calculated both the total weight and the center of gravity of the entire generator.

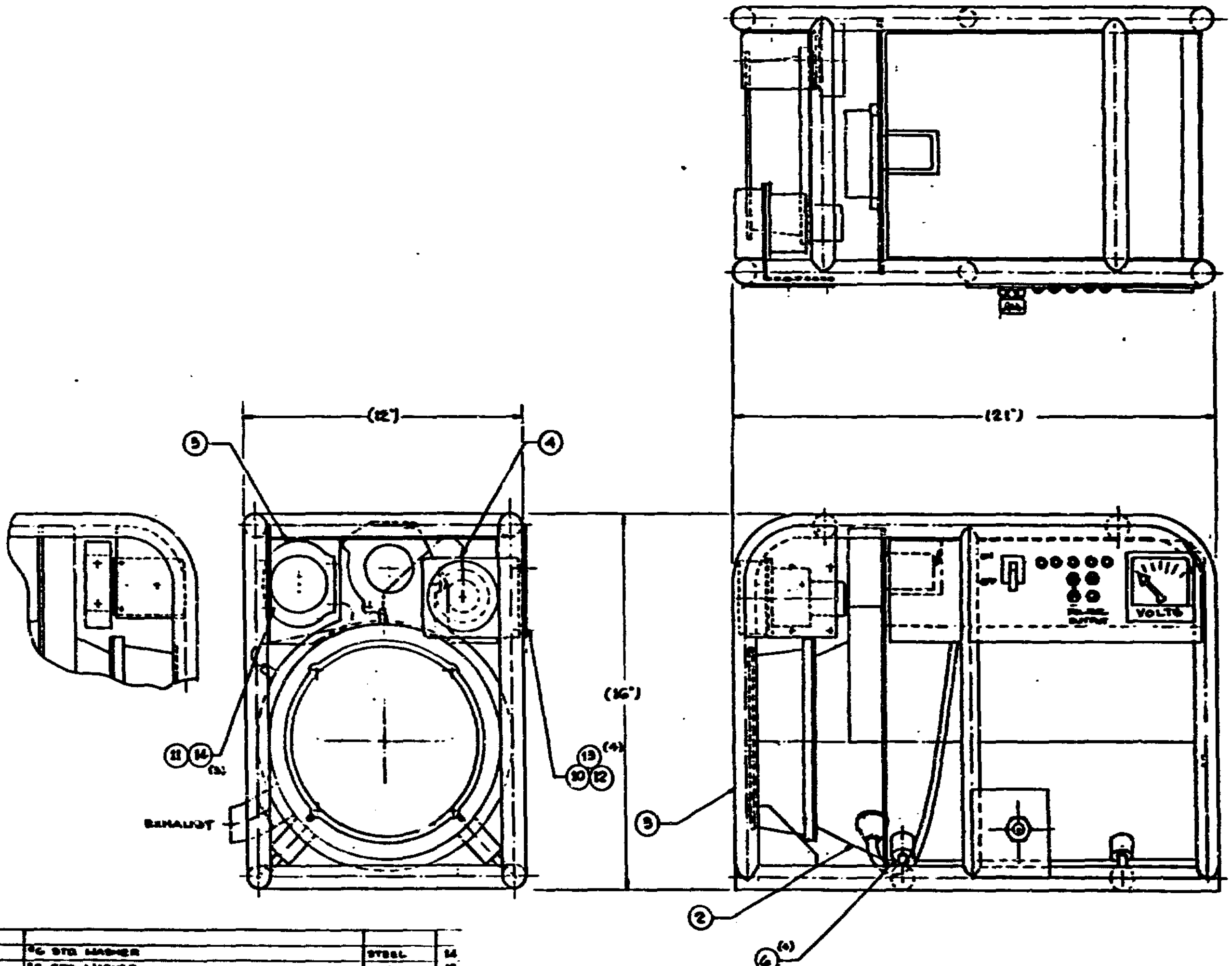
The current weight estimate for the dry generator is 51.59 pounds or about 6.59 pounds over the original weight goal of 45 pounds. We believe that we can reach the weight goal of 45 pounds.

The center of gravity is calculated to be about 5.7 inches to the right of the combustion air blower mounting plate and about 0.8 inches above the centerline of the PCU. Such center of gravity information can be used in Phase II to determine handling procedures and lifting points as well as shock absorber placement and specification and the units response to shcok and vibration.

13.2 Generator Size Estimate

The overall dimensions of the generator are in large part determined by the heat transfer design of the system. Several inches of both generator width and height are as a result of the heat transfer fins on both the hot side and cold side of the generator. More detail system design is required to optimize the design of these heat transfer surfaces than was available during Phase I.

The overall dimensions for the generator as shown in Figure 13.1 are 12 inches wide by 21 inches long by 16 inches high. This results in a volume of 2.33 $ft.^3$. This means that the existing



		3		#6 STD. WASHER	STEEL	14
		4		#8 STD. WASHER		13
		4		#8-32 HEX NUT		12
		3		#6-32 x 1/2" LG. FIL. HD. SCREW		11
		4		#8-32 x 1/2" LG. FIL. HD. SCREW	STEEL	10
						9
						8
						7
		4		SHOCK MOUNT		6
		1	[illegible]	PUMP	[illegible]	5
		1		BLOWER		4
		1	[illegible]-1	CAGE ASSY.		3
		1	[illegible]-1	500 WATT GENERATOR ASSY.		2
		X	-1	ASSEMBLY		1

Figure 13.1 Layout of 500 W Generator

volume must be reduced by about 35.6% to reach the volume goal. A sensitivity study was performed to determine what this means in terms of actual dimensional changes. Table 13.1 lists the effect of individually changing each of the major dimensions while Table 13.2 shows the effect of jointly changing all dimensions.

Table 13.1

Effect of Individual Dimensional Changes on Volume

Change Item	1 inch	2 inch
Width	8.2%	16.55%
Length	4.5%	9.39%
Height	6.12%	12.37%

Table 13.2

Effect of Changing All Dimensions Equally on Volume

1 inch	18.04%
2 inch	33.9%

From Tables 13.1 and 13.2 it can be seen that less than a 2 inch change in all dimensions is required to meet the volume goal. Also, height and width reductions provide the quickest way to reach the goal. It is the height and width that will change if the heat transfer fins can be reduced. As a result we feel that the goal of 1.5 $ft.^3$ for the generator can be obtained during Phase II.

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14.0 I.R. Signature

There are two major sources of I.R. signature and one minor source of I.R. signature from the 500 Watt generator. The major sources are the exhaust from the generator burner and the cooling air outlet from the heat sink.

14.1 Exhaust System

The exhaust temperature for the generator in its non-recuperated configuration is 700°C. In addition, the plume from the exhaust will contain both CO_2 and H_2O vapor. The CO_2 has strong emission bands in the 2.7μ and 4.4μ wave lengths while the H_2O vapor emits a strong 2.7μ band. These bands will stand out against the background of the normal atmosphere because they will be at higher concentrations than in the background.

The signature from the exhaust can be decreased by several methods. One method would be to use a recuperator which would lower the exhaust temperature and increase the system efficiency as was shown in Figure 10.2. This would increase both the length and weight of the generator.

Additional air flow from the cooling fan could be used to dilute the exhaust gas and bring its temperature down. This may not be a very efficient method of reducing temperature because it would require a higher powered cooling fan, which would increase the amount of fuel burned.

The ease of detecting the exhaust is directly proportional to the plume area of the exhaust. This area can be decreased by making multiple exhausts rather than a single exhaust. Such a modification would only have minor weight or size consequences.

A source of exhaust I.R. signal would be the hot metal of the exhaust pipe. This signature can be reduced by film cooling the interior of the end of the pipe. The exterior temperature of the exhaust pipe can easily be reduced by the application of insulation.

It is important that the exhaust plume or plumes from the generator are not directed at another body. This would heat the body and create a new and different signature.

14.2 Cooling System

The signature from the cooling system will be more difficult to detect because it will not produce significant CO_2 and H_2O bands because they will be at the same concentrations as the background. The temperature of the cooling air plume will be at about 73°C compared to a 20°C background. The lack of more highly concentrated CO_2 and H_2O bands should make it difficult to detect the plume unless the plume strikes and warms a nearby solid body.

The warm materials in and around the outlet area could provide a good signal source. The source strength would depend on the angle with respect to the plane of the cooling outlet opening. This signal could be reduced by shielding the heat transfer fins from direct view and coating the remaining surfaces with a material with low emissivity in the long wave I.R. region.

15.0 Reliability

An overall reliability goal has been taken to be 10,000 hours mean lifetime. At this point estimates support a 6 month lifetime in continuous operation and an 8 month life in daily cyclic service.

The objective has been to design a simple yet reliable system to incorporate the thermoelectric generating modules, which are by themselves inherently reliable. The modules are static power converters and as such have no wear mechanisms. Modules of thermoelectric converters operating in their design temperature range show no degradation and demonstrate long operating life. They are sufficiently rugged to withstand handling of fabrication and loads in service that might initiate flaws leading to failure.

15.1 Module Reliability

Overall reliability is addressed in two parts. First, the reliability of the thermoelectric modules is considered. The generator is made up eighteen modules connected to produce 24 volts total output as shown in Figure 15.1. This connection arrangement provides some redundancy. The remainder of the generator system is comprised of switches, pumps, fans, *etc.* for which there is no redundancy provided.

There is no specific data base for the thermoelectric modules that would be used in this generator, but similarly designed modules currently are accumulating hours on test. Thermoelectric generators developed for space power use have an impressive record of reliability, having demonstrated little or no degradation over tens of years of service. The mean time between failures (MTBF) in a statistical population of modules is estimated to be between five and 20 years. For the extremes of this range the reliabilities calculated for the 18 modules are shown in Table 15.1. Note that failure is tabulated two ways: failure to produce rated output, that is failure of one module and consequent loss of a fraction of output, and failure to produce any output, which is failure of the

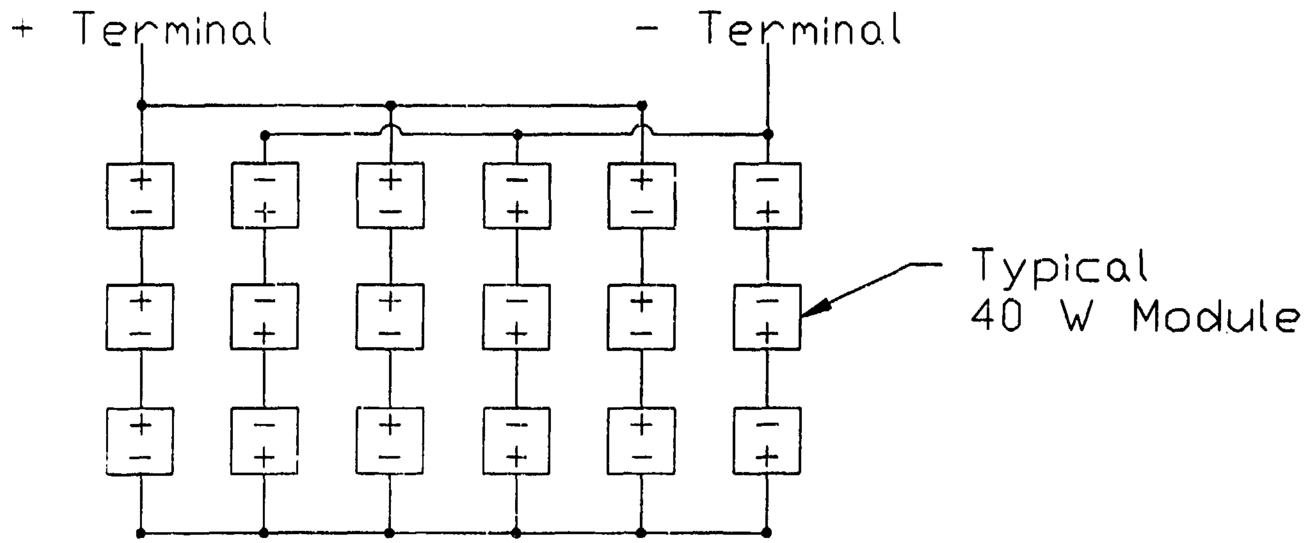

Figure 15.1 Module Connection for 500 W Generator

consequent loss of a fraction of output, and failure to produce any output, which is failure of the minimum number of modules to go totally open circuit. Numbers are also shown for both a straight 3 X 6 array and for the 3 X 6 array with central cross-connection (which is a series-connected pair of 3 X 3 arrays). The latter is the reference design. As the numbers show, the cross-connected design has vastly improved reliability for either loss of some or all output compared to the straight 3 X 6 array.

Table 15.1
Module Reliability

Thermoelectric Module	MTBF = 5 yr	MTBF = 20 yr
	RELIABILITY (per year)	
module	0.819	0.951
loss of output		
array of 3 x 6 (33% loss)	0.301	0.741
MTBF	7300 hr	29,000 hr = 3.3 yr
array with cross-connection (17% loss)	0.549	0.861
MTBF	14,600	58,000 hr = 6.7 yrs
loss of all output		
array of 3 x 6	0.659	0.983
MTBF	2.4 yr	57 yr
array with cross-connection	0.955	0.986
MTBF	22 yr	72 yr

15.2 System Reliability

The second part of the analysis is a quantification of the overall system including the modules. The generator is to operate intermittently, and at this point in the design and development there is no prescribed mission profile. However, quantitatively predicted overall reliability appears to be satisfactory. The goal of high reliability of the generator system means quantifying three potential negative system outcomes: failure to start on demand, mean time of operation before failure, failure to stop on demand.

If one considers the three failure categories in reverse order, it is intuitive that the failure to stop on demand is the least likely concern. In reality the failure to stop is almost a non-problem, because there are various alternative ways to shut-off the generator manually. However, failure to stop can be a serious matter in application if a unit were to continue operating uselessly and consuming valuable fuel. Calculation of failure to stop is simply based on the failure rates of commercial items that would be used for the stop switch and associated relays. The resulting rate is 0.999995 per demand, or one in 200,000 tries.

In a calculation of the mean time of system operation before failure, the important factors for comparison are the MTBF for the least reliable components required for continuous operation. A review of generic failure rates for types of components indicated that the most critical are related to the fuel supply. The most likely contributor to limited lifetime is running out of fuel, and the second most likely is the failure of fuel to reach the generator due to a blocked fuel filter. For the present analysis it is assumed that the generator will be subject to a maintenance program that will assure against failures of these types.

The balance of the system is made-up of components that can be variously classified. Passive electrical or mechanical components (such as electric cable and air flow passages) and electronics (such as the control subsystem) have inherently high reliability. Switches, relays and batteries also have high reliability once in steady operation. From among these the least reliable are identified as the two interlock sensors, which have a typical MTBF each of 10^6 hours and the seven interface relays that control the electromechanical components and ignition, for which the MTBF is taken to be $2x10^5$ hours. The combined reliability is then 27,730 hours MTBF for the electronics, sensors and relays.

Of concern are the electromechanical components, and the four essential to generator operation are listed in Table 15.2. In the table are the MTBF values from vendor literature for the four commercially available generator components. Their total MTBF alone is 7143 hours, which already compromises the system goal. It is proposed that for military procurement these components could be selectively chosen to survive double the lifetimes quoted by the vendors, and so as a group the MTBF would be 14,286 hours. This value combined with the electronics, sensors and relays results in an MTBF of 9310 hours.

Table 15.2
Failure Rates of Electromechanical Components

	MTBF
Fuel pump	150,000 hr
cooling air fan	30,000
combustion air fan	20,000
atomizer air pump	20,000
	7143 hr

For the purpose of combining the thermoelectric modules into the system calculation, the number used is the failure to produce rated power for the array with cross-connection of modules with an individual life of 20 years MTBF. From Table 15.1 this is 58,000 hours MTBF for the thermoelectrics. Combined with the MTBFs for the electromechanical and the electronic components the resulting system MTBF is 8038 hours.

The one element of the system that has been left out of this analysis thus far is the output power inverter/regulator. Unfortunately, these units have a quoted MTBF of only 10,000 hours. In combination with all of the other system elements the total MTBF that results is 4456 hours, which equates to 6.1 months of continuous operation for 50% of generators.

Failure to start has been calculated using generic numbers for the switches, sensors and relays that function. Similarly, the reliability of the control electronics, the ignition control and igniter have been included. The reliable supply of starting electric power is not included, because it is assumed that a program of maintenance will assure that there is one or more battery with sufficient capacity to power the initial demand of the electronics, the fuel pump, the atomizer, the igniter and the combustion air fan. The resulting rate calculated is 0.9998 per demand, or one in 6250 tries.

Table 15.3 summarizes the results of the system reliability calculation. These results can be combined for an overall illustration of the reliability if one assumes a scenario of turning the generator on daily, running it for 12 hours and turning it off. The combined reliability rate from the numbers in Table 15.3 is 0.997 per day. The meaning of this number is elaborated in Table 15.4. In a statistical population of generators the average generator would operate in that cycle for 8 months. In such a population 1 out of 1000 generators would only last 8 1/2 hours, but 99 out of 100 would still be operating at 3.6 days, and only 10% would fail before 37 days.

Table 15.3
Summary of Reliability Calculation

Failure to Start		R = 0.9998 per demand
Failure to Run		
MTBF	thermoelectric	58,000 hr
	inverter	10,000
	all else	9,332
		4,456 hr
		= 6.1 months
Failure to Stop		R = 0.999995 per demand

Table 15.4
Reliability in Daily 12 Hour Cycle

Confidence	Lifetime
.5	243 days = 8 months
.9	37 days
.95	18 days
.99	3.6 days
.999	0.35 days = 8.5 hours

16.0 Conclusions

A small highly reliable 500 Watt thermoelectric generator can be built to meet the design goals for this program. The detail design, construction and operational test of such a prototype generator can be accomplished within the funding and time constraints of a Phase II SBIR program. Such a generator would be designed to use a number of logistically available liquid hydrocarbon fuels and should provide a highly reliable power source.

Safe operation of the generator will require a minimum about of training because of the microprocessor based control system. This control system will be designed with a built-in self diagnosis function which will minimize maintenance problems by identifying the source of a operation malfunction.

The reliability of the generator is limited by the reliability of the DC/AC inverter system. Both the overall system and the available power will increase if the generator can be operated in the DC mode rather than the AC mode.

The 500W generator will require a fuel flow of about 0.41gal/hr. The fuel consumption of the generator can be decreased up to 36% by including a recuperator to transfer energy from the exhaust to the incoming air. Including a recuperator will increase both the weight and volume of the generator and is therefore not desirable for a minimum weight and volume system.

All of the auxiliary components required to build the generator are commercially available. Additional testing and/or minor modification will be required to prove that some of the less costly components are reliable enough to use in the generator system.

The metallurgically bonded thermoelectric module used in the generator requires some further development. This development should be completed because it has the potential to provide a module which has lower cost, is more efficient, and can be easily used in thermoelectric generators with both higher and lower power ratings.

17.0 Recommendations

Hi-Z recommends that the development of the small 500 Watt thermoelectric generator be continued in a Phase II program. A prototype generator should be build and performance tested during Phase II which uses the metallurgically bonded planar lead telluride modules which are segmented to maximize the energy conversion efficiency.

The Phase II development effort should include detail engineering analysis which is required to reduce the size of the generator to meet the original design goals. Phase II should also continue the investigation of commercially available system components which are both highly reliable and less costly. This portion of the program would include the purchase and test of less costly commercial components such as fuel pumps which appear to have potential meeting the reliability requirements but either do not have sufficient reliability test data or require minor modification to achieve high relialibity.

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